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Validation of Meta Motion IMU Sensors Through Measurement of Knee Angles During Gait

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VALIDATION OF META MOTION IMU SENSORS THROUGH MEASUREMENT OF KNEE ANGLES DURING GAIT

by

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ABSTRACT

VALIDATION OF META MOTION IMU SENSORS THROUGH MEASUREMENT OF KNEE ANGLES DURING GAIT

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The implementation of inertial measurement units (IMU) in the biomechanical field has become increasingly popular due to their robustness, simplicity, accuracy, and the ability to move research out of a lab and into the real world. In this study, the MetaMotion IMU sensors are assessed for validity against a dynamometer and the Vicon motion capture system. Both systems have proven their measuring accuracies in the biomechanics world and are used as the truth source for this validation study. In the first part of this study, the sensors are assessed for various common sensor errors. Individual sensor components of the IMU, the accelerometer and the gyroscope are validated against the dynamometer by measuring orientation and angular velocity, respectively. In the second part of this study, three subjects performed several gait trials while tracking their movements simultaneously with the MetaMotion sensors and the Vicon system. A dynamic sensor to segment alignment method is adopted in an attempt to accurately define the MetaMotion orientation with respect to the body's segments. Sensor fusion is used to filter the IMU data by combining the measurements of the accelerometer and gyroscope to report orientation presented as knee angles. A statistical agreement assessment is performed at peak values to predict the accuracies and reliability of the MetaMotion sensors when compared to the dynamometer and Vicon systems. Results suggest the possibility of using MetaMotion sensors in biomechanical research studies in place of modern testing techniques such as optical motion

capture. Limitations are expressed and future work is suggested to better account for types of sensor error, test various movements and develop alignment methods for more complex joints.

I dedicate this thesis to my husband, Ryan, who provides me unwavering support in all my aspirations as well as my siblings, Kim, Nick, and Amanda, who drive me to pursue my goals with integrity. To my mom and dad for all their sacrifices and teachings over the last 26 years and for always believing in me.

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CHAPTER I

INTRODUCTION

Optical motion capture is currently the gold standard and perhaps the most adopted technique in biomechanical analysis (Camomilla et al., 2018). However, optical tracking systems require an expensive camera system with several cameras, often many individual markers, and a large capture volume (Camomilla et al., 2018). The only feasible way to use these systems is in a laboratory setting that is strictly dedicated to motion capture, not to mention the accuracy of obtaining kinematic through optical motion capture directly relates to correct placement of each marker and the ability to reduce soft tissue artifacts (Camomilla et al., 2018). This technology severely restricts the type of data researchers can collect as well as the population that can be brought in for testing. For example, biomechanists are unable to realistically evaluate cross country runners running miles along the street or alpine skiers racing down a mountain. As technology advances, biomechanics, engineers, therapists, and other professionals are looking to move motion capture outside of a laboratory setting, into real life settings. One way that engineers have developed means for flexible tracking capabilities is through inertial measurement unit (IMU) sensors, such as the MetaMotion sensor (*Metamotionrl, San Francisco, CA*).

IMU sensors typically consist of triaxial accelerometers, gyroscopes, and magnetometers in their own three-dimensional local coordinate system (Seel et al., 2014). The accelerometer components detect linear acceleration over time in all three axes. The gyroscope components detect rotational motion at an angular rate about each axis. The magnetometer measures the direction of the magnetic field, such as earth’s magnetic field, however that is not always the case. Using a combination of these sensors, the IMU is capable of reporting an object’s rotational velocities and orientation, commonly referred to as pitch, roll and yaw (Benson et al., 2022).

IMUs are used well beyond the field of biomechanics and are found in everyday devices such as smartphones, robots, drones and more. IMUs do not require the use of the magnetometer, however the use of a magnetometer can help compensate for sensor drift overtime (Weygers et al., 2020). Unfortunately, the magnetometer comes with its own limitations since it can be skewed by outside magnetic sources (Binnie et al., 2021). The magnetometer becomes very unreliable when put in an environment with ferromagnetic or electromagnetic surroundings (Schall et al., 2015). Because of this limitation, many biomechanical studies involving IMU sensor tracking choose to omit the use of the magnetometer and only use the accelerometer and gyroscope to determine position and other kinematic variables (Benson et al., 2022).

A proven theory for determining angular velocity and orientation from accelerometer and gyroscope sensor readings is known as sensor fusion (Segarra et al., 2019). Sensor fusion is achieved by filtering and combining each individual sensor output. Studies utilized different sensor fusion approaches mainly to overcome gyroscopic drift within the sensors (Roell et al., 2019). Two popular approaches when applying IMUs to human movement are known as Complementary filtering and Kalman filtering (Roell et al., 2019). A cmplementary filter is a basic low-pass, high-pass filter and relies on the frequency domain of the sensor reading (Roell et al., 2019). The Kalman filter is much more powerful and designed to predict the movement of the sensor based on prior system knowledge (Nez et al., 2018). The Kalman filter has become largely adopted in environments with noisy environments, including human movement (Nez et al., 2018).

IMU systems are able to estimate the sensor's coordinate system with respect to the global coordinate system and this orientation is commonly represented by a quaternion, a rotation matrix or Euler angles (Seel et al., 2014). One challenge presented to IMU human movement tracking is accurately defining the sensor to segment orientation without the need for assistance by optical motion capture or fixing degrees of freedom of complex joints. When it comes to kinematic applications, there are several methods for understanding the sensor orientation with respect to the segments of interest (Fan et al., 2021). For example, some researchers will use IMUs alongside live motion capture to determine real time sensor to segment orientation. Another method includes averaging previously collected motion capture data to estimate segment alignment (Fan et al., 2021). Other researchers will make assumptions about the joint of interest by fixing an axis or assuming zeros in certain postures (Favre et al., 2008). Newer procedures advertise the use of functional movements that capture the segment's motion throughout known and repeated movements (Mascia et al., 2022). This method estimates the movement about a joint axis, and when combined with static calibration, can accurately estimate sensor to segment orientation (Mascia et al., 2022). Functional calibration protocols have reported high precision and repeatability as well as remove the need for optical motion capture assistance (Mascia et al., 2022).

The MetaMotion sensors are advertised as portable tracking devices suitable for research and clinical studies relating to gait analysis, fast moving objects or humans and other applications. The IMU consists of a gyroscope, accelerometer, magnetometer, barometer and temperature sensors. Combined they offer a snapshot of the device in space that can be studied for a variety of applications. The problem with the MetaMotion and other IMU sensors alike is that there lacks validation data proving the capabilities of these sensors (Binnie et al., 2021).

Previous studies claim that there is a need for validation methods and task specific IMU based biomechanical models to distribute IMU sensors into the motion capture industry (Weygers et al., 2020). MetaMotion sensors are unique to the field in that they are one of the more affordable and durable units, opening up opportunities to reach several researchers and those studying in rugged, unpredictable environments. To date, there are no known studies specifically validating the MetaMotion sensors for lower body kinematics. To test this means the MetaMotion sensors are validated against one of the industry's most accepted biomechanical analysis tools for studying kinematics, an optical tracking system.

The purpose of this study is to validate the MetaMotionR sensor, through calculation of knee angles to determine if MetaMotion sensors are a reliable tool for biomechanics research applications. The practice of using IMUs to measure kinematics is becoming more common due to their affordability, accuracy, and setup capabilities. Validating these sensors will provide cheaper, more robust tools for collecting kinematic data in field applications when access to biomechanics labs is limited.

This research is intended to validate MetaMotion sensors as well as offer a calibration and sensor fusion method for using IMUs to study lower body kinematics. The triaxial accelerometer and gyroscope units within these sensors were tested and analyzed in dynamic conditions. Their values are analyzed individually and through sensor fusion and compared to industry accepted tools. The MetaMotion sensors were validated against two systems: the HUMAC® NORM™ Dynamometer (CSMI, Salem, NH) and the Vicon Vantage Motion Capture (Vicon, Centennial, CO) system. The dynamometer is a system that measures human performance through joint isolated static and dynamic movements (Hegedus & Stevens-Lapsley, 2022). In this study, the MetaMotion's accelerometer and gyroscope are validated independently against the dynamometer's position and angular velocity, respectively. After the individual components are evaluated against the dynamometer, the sensor is tested during gait trials against the Vicon motion capture system. The Vicon system is a reflective marker motion capture system that is accepted in the biomechanics industry for its precision and accuracy in tracking abilities (Vantage, 2021). In the second half of this study, the MetaMotion sensors, a calibration method and sensor fusion techniques used to calculate knee angles are validated against knee angles derived from the Vicon system and Visual 3D during gait. The results from this study may prove that IMU sensors offer cheaper, flexible yet still precise tracking abilities to the biomedical industry.

CHAPTER II

DYNAMOMETER VALIDATION METHODS

IMU Sensor Errors

Common errors associated with IMU sensors include drift, noise and bias (Weygers et al., 2020). Understanding all possible error measurements associated with MetaMotion sensors allows researchers to identify, estimate and correct these errors during data processing.

Sensor drift accounts for frequency changes over time that may be due to changes in pressure, temperature or vibration. Sensor noise comes from the varying output of the sensors depending on its external conditions. Longer trial runs or rapidly changing environments could increase the chances of these sensor errors. Controlled settings combined with calibration techniques help mitigate common sensor errors.

Bias provides the offset measurement used when calibrating the sensor. Single-point calibration was used where the bias was subtracted from the indicated value on the sensor to achieve the actual value. Null bias is error experienced during no input. To test for null bias and to determine the offset measurement of the accelerometer and the gyroscope of the MetaMotion sensor, the sensor outputs values in a stationary, known orientation. The vertical accelerometer component should be equal to 1g and the gyroscope should be equal to 0 deg/s. This was repeated three times, allowing all three axes (x,y,z) to be tested in the vertical orientation.

Since the MetaMotion sensor does not have three flat sides that allows for stationary, vertical measurements of each axis, a cubed sensor case was designed. The sensor case (Figure 1) was designed in Autodesk Fusion 360 (Autodesk, San Rafael, CA) and 3D printed using a fused deposition modeling printer with A.S.A plastic material. The CAD drawing for the sensor cube can be found in Appendix C.

The sensor case was used to accurately position the sensor in all three orientations. To perform the static calibration trials for the sensor, the case housed the sensor and was placed in each orientation on a flat surface and accelerometer and gyroscope data were recorded. A level was used on the surface that the sensor is placed on during this phase to ensure the vertical axis is aligned with Earth's gravity (1g) as close as possible.

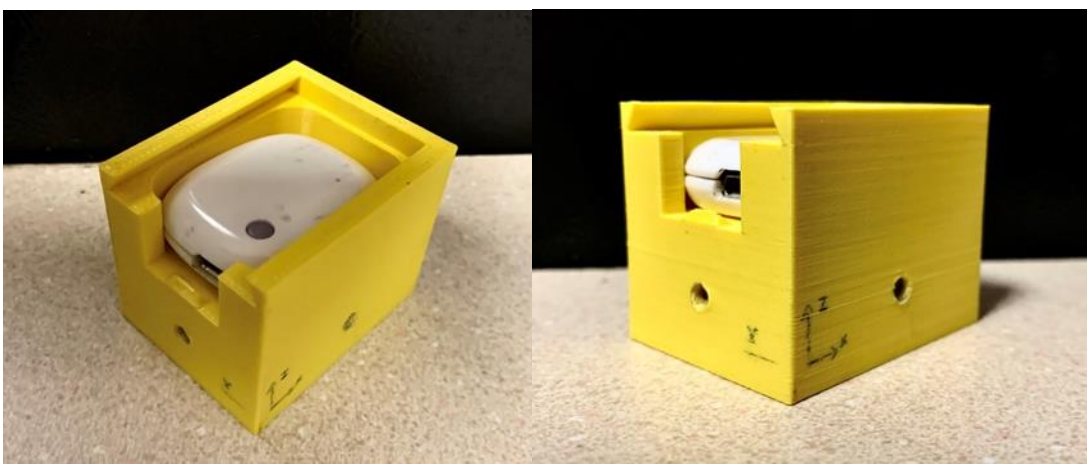

Figure 1. Sensor case designed to provide accurate sensor calibration on all three axes.

The acceleration and angular velocities obtained during this phase were recorded, averaged over one second intervals and compared to their expected values. Null bias, b, was found by comparing acceleration values to 1g (Equation 1) and gyroscope values to 0 deg/s (Equation 2).

$$acc_x = 1g + b_{ax} \qquad \text{Equation 1}$$

$$gyr_x = 0\frac{deg}{s} + b_{gx} \qquad \text{Equation 2}$$

where x represents which axis was placed in the vertical orientation.

Bias repeatability, also known as turn on error, is when null bias changes between power cycles of the sensor. To account for this bias, before each data collection session or with each reboot of the sensor, the sensor was calibrated using the sensor cube in Figure 1. Bias was calculated using Equations 1 and 2 and individual axis offsets were used for individual subjects and each time the sensor was power cycled.

Dynamometer Setup

Bias stability is sensor bias during dynamic movements over time. To measure bias stability, the MetaMotion was validated against the HUMAC® NORM™ dynamometer.
To test for bias stability, the MetaMotion is validated against the HUMAC® NORM™ dynamometer. The dynamometer is used as a tool to create known and repeated positions and angular velocities. The sensor case was tightly secured to the dynamometer's arm using a screw in an attempt to reduce vibration from the dynamometer (Figure 2).

Figure 2. Sensor mounted to dynamometer for bias stability testing.

The dynamometer was programmed to run three dynamics tests at three angular velocities: 100 deg/s, 300 deg/s and 500 deg/s from 0 to 150°. These velocities are chosen with physiological applications in mind as well as understanding the range of the sensor. 100 deg/s and 300 deg/s represent physiological movements in gait and upper body movements. 500 deg/s was measured to test the range of the MetaMotion sensor, as it is the max speed the HUMAC® NORM™ dynamometer will allow to program (Hegedus & Stevens-Lapsley, 2022). The dynamometer freely moved the sensor at each velocity through a range of motion from 0 to 150 degrees, the maximum range of motion of the dynamometer, five times. The first rotation was ignored in data processing since the dynamometer required an initial application of outside force to begin the test. The sensor case was mounted on all three axes to test the angular velocities of each axis. The dynamometer testing is performed three times for all three speeds in all three orientations for a total of 27 sets, 9 per orientation. Dynamometer data, which included rotation (degrees) and angular velocity (deg/s), were recorded at 100Hz. MetaMotion sensor data including accelerometer (g) and gyroscopic (deg/s) data are also collected at 100Hz.

The dynamometer recorded values for orientation (degrees) and angular velocity (deg/s) over time. The MetaMotion sensor recorded linear acceleration (g) and angular velocity (deg/s) through the use of its accelerometer and gyroscope, respectively. In this study, the accelerometer was validated against the dynamometer orientation readings (degrees) and the gyroscope was validated against the dynamometer angular velocity readings (deg/s). MetaMotion readings were first corrected for bias using the methods described alongside Equation 1 and 2. Equation 3 was used to convert accelerometer readings from g to degrees. The MATLAB function, *acosd*, calculates the arccosine of the sensor readings and converts values from radians to degrees. Only one axis was used to determine orientation for each trial to isolate each axis within the sensor. This would ensure all axes performed with the same accuracy and aligned as expected within the sensor.

$$acc(degrees) = acosd\left(\frac{acc(g)}{1}\right) \qquad \text{Equation 3}$$

MetaMotion readings were then passed through a bandpass filter in MATLAB to remove sensor noise. Figure 3 shows a sample of the raw and filtered accelerometer and gyroscope data taken from one of the trials run at 100deg/s.

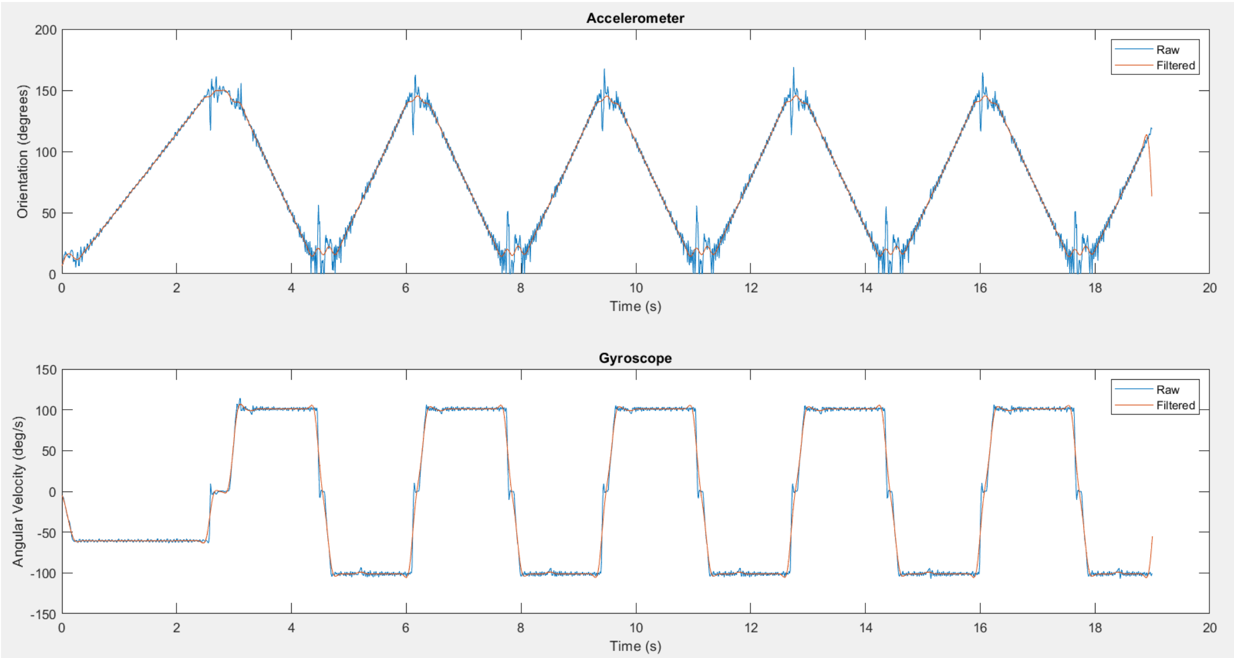

Figure 3. Sample of raw and filtered accelerometer and gyroscope readings.

The dynamometer does not have a universal time stamp therefore time syncing the dynamometer readings with the MetaMotion readings becomes nontrivial. Therefore, the two data sets were cross correlated using the Matlab function *xcorr*. *xcorr* measures the similarities between two discrete time sequences, instead of conducting a direct comparison of synchronized data sets. The data sets are then cropped to the same size for further processing. Because the first trial/last trials are ignored, there was no loss in data.

CHAPTER III

DYNAMOMETER VALIDATION RESULTS

Figures 4-6 display a sample of the processed MetaMotion's accelerometer and gyroscope data against dynamometer data for trials at 100 deg/s, 300 deg/s and 500 deg/s.

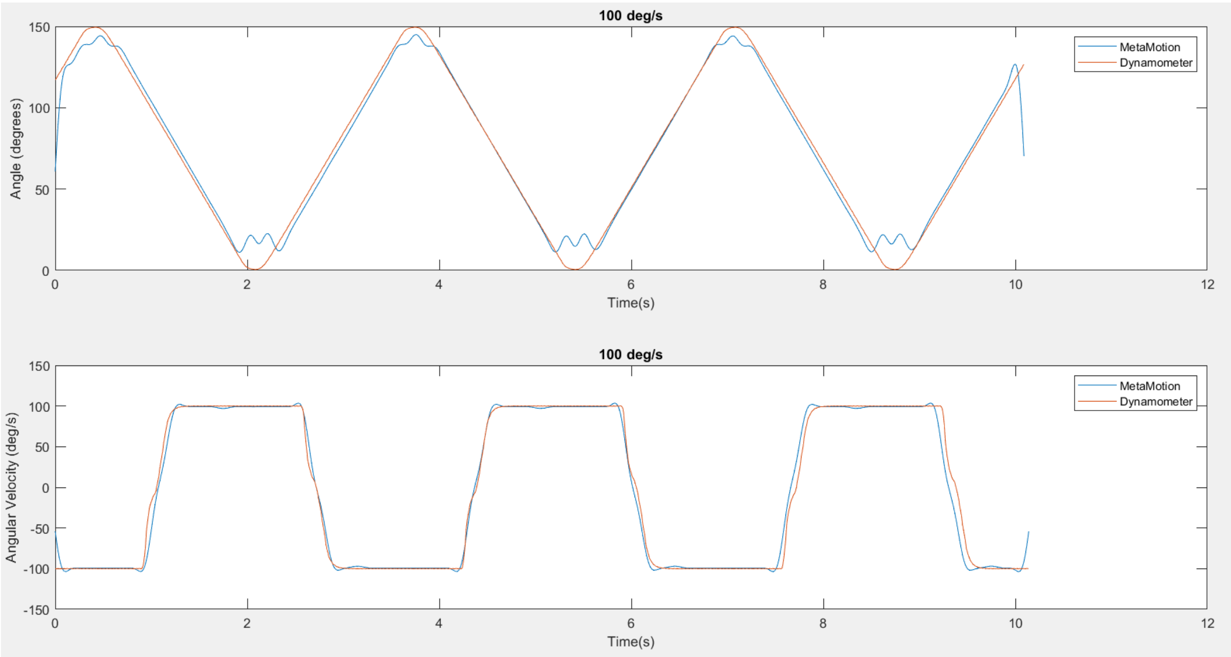

Figure 4. MetaMotion and dynamometer orientation and angular velocity for 100 deg/s about the z-axis.

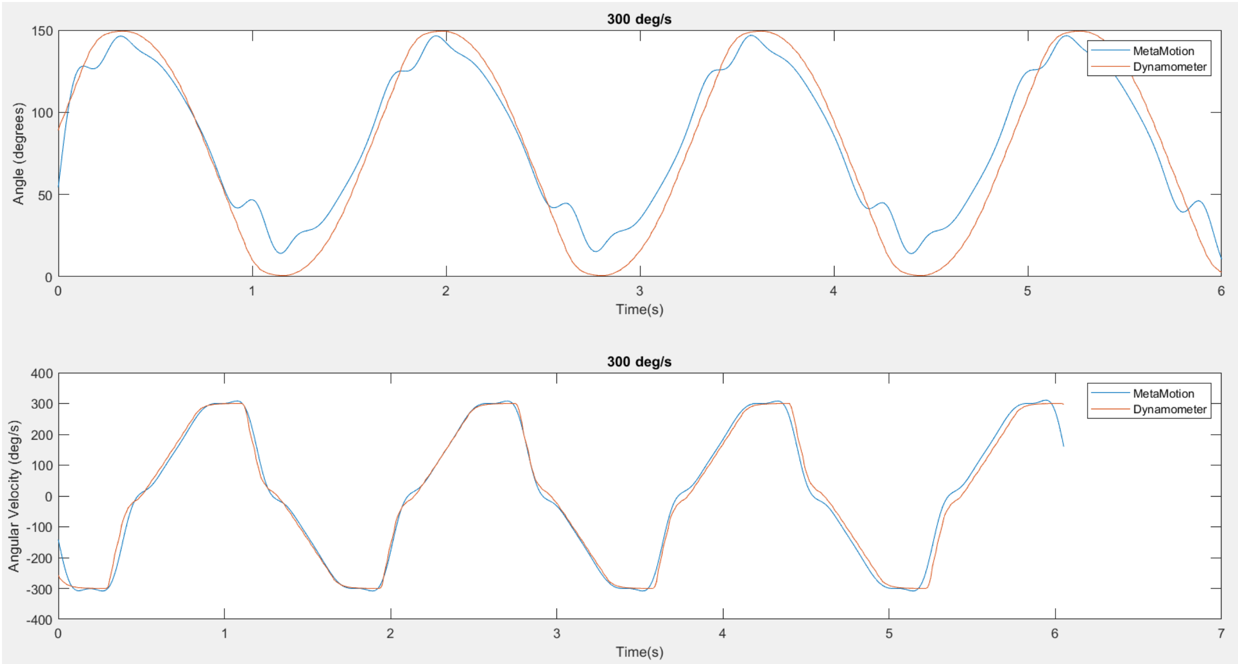

Figure 5. MetaMotion and dynamometer orientation and angular velocity for 300 deg/s about the z-axis.

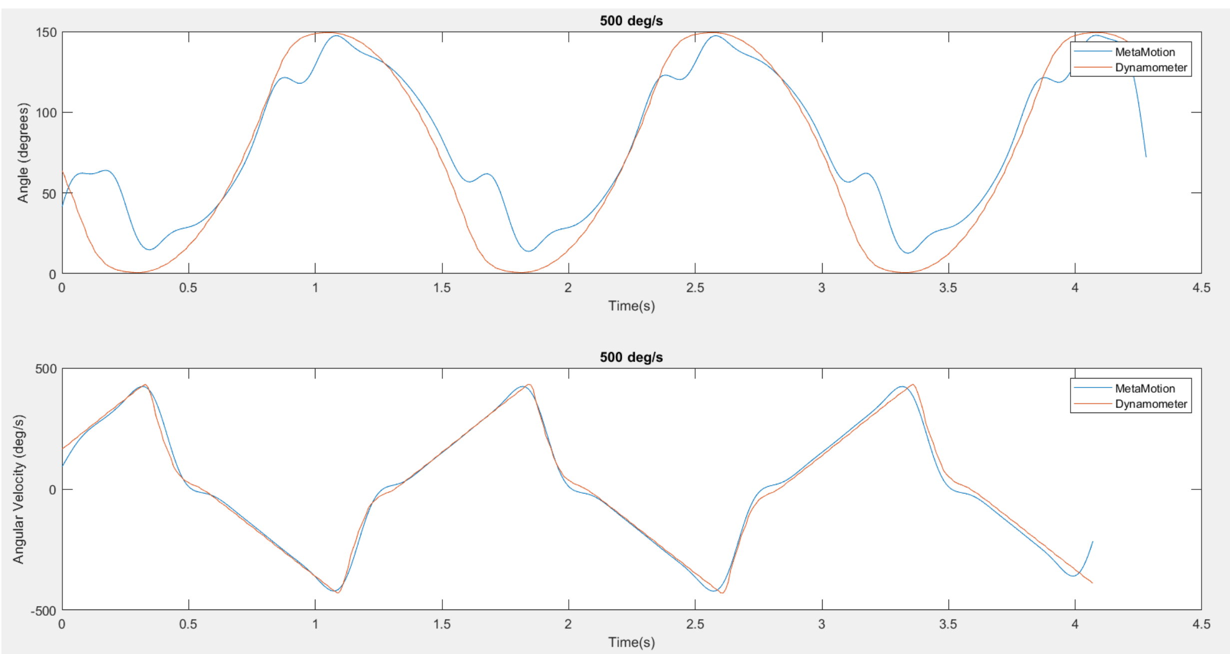

Figure 6. MetaMotion and dynamometer orientation and angular velocity for 500 deg/s about the z-axis.

At an initial glance of the processed data it is clear to see that the accelerometer did not reach the peak angles of the dynamometer. This may be due to the abrupt change of direction of the dynamometer creating vibration and drift within the accelerometer. It was noticed during data collection, that the dynamometer’s arm would shake as it reached the top and bottom rotations before changing direction.

Due to the time synchronizing limitations, only peak orientations and angular velocities were compared to assess validity of the MetaMotionR sensors. After the trials were cropped, maximums and minimums values for position and angular velocity were calculated for each trial and axis and are displayed in Table 1. There were no significant differences across the three axes therefore that variable was removed from data analysis.

Table 1. Minimum and Maximum values of the dynamometer and MetaMotion accelerometer and gyroscope.

Accelerometer				*Gyroscope*			
Minimum		**Maximum**		**Minimum**		**Maximum**	
100 deg/s				*100 deg/s*			
Dyno	**Meta**	**Dyno**	**Meta**	**Dyno**	**Meta**	**Dyno**	**Meta**
0.44	13.98	150.00	150.04	-100.13	-105.57	100.13	106.86
0.44	14.29	149.50	145.75	-100.13	-105.77	100.13	105.59
0.44	9.12	149.50	146.05	-100.13	-105.59	100.13	105.63
0.50	13.94	149.88	146.93	-100.13	-103.36	100.13	103.34
0.50	13.71	149.75	146.87	-100.13	-103.44	100.06	103.32
0.44	6.65	149.81	147.21	-100.13	-103.24	100.06	103.41
0.50	11.16	149.50	144.97	-100.13	-103.61	100.13	103.48
0.56	10.82	149.50	144.55	-100.13	-103.51	100.13	103.58
0.56	11.26	149.50	150.71	-100.13	-103.54	100.13	103.45
300 deg/s				*300 deg/s*			
0.56	12.69	150.13	151.15	-299.88	-307.50	299.81	307.12
0.56	11.97	149.38	147.22	-299.81	-309.91	299.81	307.27
0.63	13.70	149.38	153.56	-299.81	-307.56	299.81	307.28
0.63	12.84	150.31	158.35	-299.81	-314.45	299.88	314.52
0.63	12.64	150.31	148.68	-299.88	-314.39	299.81	314.58
0.56	11.30	149.63	148.49	-299.88	-314.44	299.81	314.64
0.69	10.62	149.38	146.75	-299.81	-308.35	299.81	311.02
0.69	13.62	149.38	146.96	-299.81	-308.31	299.81	308.19
0.69	13.42	149.38	146.96	-299.81	-311.83	299.81	310.69
500 deg/s				*500 deg/s*			
0.63	12.56	149.94	150.91	-429.63	-419.19	431.94	430.41
0.63	13.16	149.38	148.56	-432.31	-418.90	431.75	421.53
0.63	12.38	149.38	147.72	-430.06	-419.51	432.81	421.46
0.63	7.39	149.88	149.05	-430.44	-431.53	433.06	429.12
0.63	12.12	150.19	149.56	-431.25	-431.32	432.69	428.93
0.69	11.69	150.38	149.27	-431.13	-431.64	431.38	429.46
0.69	12.71	149.38	147.66	-430.31	-421.76	432.88	423.78
0.69	12.14	149.38	146.85	-430.44	-421.43	432.50	423.76
0.69	12.14	149.38	146.44	-431.06	-422.01	433.50	424.10

To quantify error of the sensors, the MetaMotion's accelerometer and gyroscope against the dynamometer, a statistical analysis for assessing agreement was performed (Martin Bland & Altman, 1986). The goal of this assessment was to determine the differences found between the MetaMotion measurements and the dynamometer and determine if the MetaMotion could serve as a reliable tool for measuring orientation and angular velocity. Equation 4 calculated the mean difference ($\underline{d}$) by subtracting the mean of the MetaMotion values from the mean of the dynamometer values. The mean difference was used to determine the differences found between the MetaMotion and dynamometer at their minimum and maximum values. Equation 5 calculates the standard deviation of the differences (s) to evaluate the spread in differences between the two systems. Finally, the lower and upper “limits of agreement” are found by $\underline{d} \pm 2s$ (Equation 6).

Mean Difference: $\bar{d} = M(dyno) - M(meta)$ Equation 4

Standard Deviation of Difference: $s = \sqrt{\frac{\Sigma(x_i - \mu)}{N}}$ Equation 5

where x_i is the difference in measurements, μ is the population mean and N is the sample size.

Limits of Agreement: $"limits\ of\ agreement" = \bar{d} \pm 2\ s$ Equation 6

Assuming the differences are normally distributed, the “limits of agreement” provide the assumption that 95% of measurements will fall within the lower and upper limits of these values. The “limits of agreement” gives quantitative values to the differences expected if a MetaMotion is used to measure orientation and angular velocity. The Bland and Altman “limits of agreement” between the dynamometer and the accelerometer are reported in Table 2.

Table 2. Limits of Agreement between Dynamometer and MetaMotion Accelerometer.

Mean Difference	-5.07
Standard Deviation	6.73
Limits of Agreement	{-18.67, 8.39}

The distribution of differences between the two systems can be depicted by plotting the average measurement between the two systems against the difference in measurements between the two systems. Figure 7 represents the dynamometer and accelerometer differences plotted against the confidence interval. The mean is plotted as an orange line and the lower and upper "limits of agreement" are plotted as green lines. The agreement assessment suggests that for an acceleration value (orientation angle), it is expected that 95% of MetaMotion measurements would fall between 18.67 degrees above or 8.39 degrees below the dynamometer or true measurement.

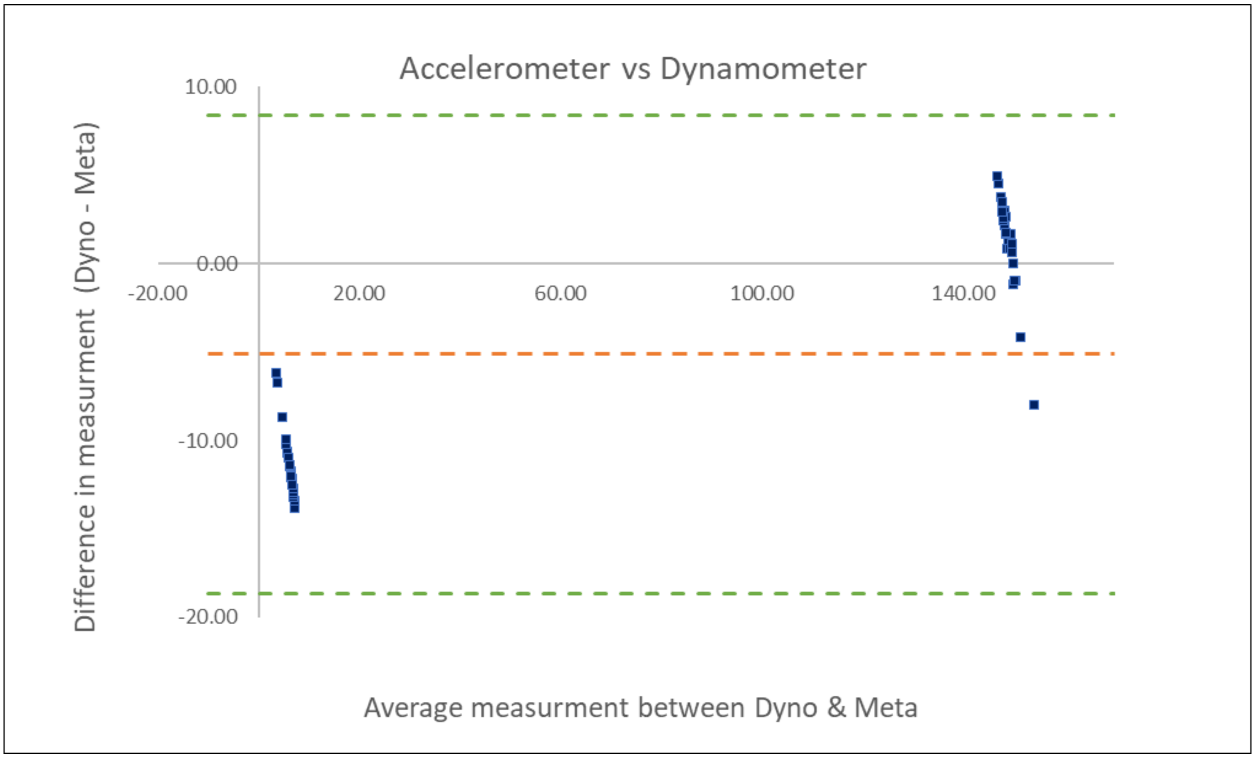

Figure 7. Difference in measurement against average measurement between dynamometer and MetaMotion accelerometer.

The same analysis was performed on the gyroscope data and present in Table 3 and Figure 8. For the gyroscope, or angular velocity, it is expected that the MetaMotion measurements would fall between 16.69 deg/s above or 16.71 deg/s below the dynamometer or true measurement. The "limits of agreement" must be assessed to determine which range is considered acceptable depending on the application of the measurements.

Table 3. Limits of Agreement between Dynamometer and MetaMotion Gyroscope.

Mean Difference	0.01
Standard Deviation	8.35
Limits of Agreement	{-16.69,16.71}

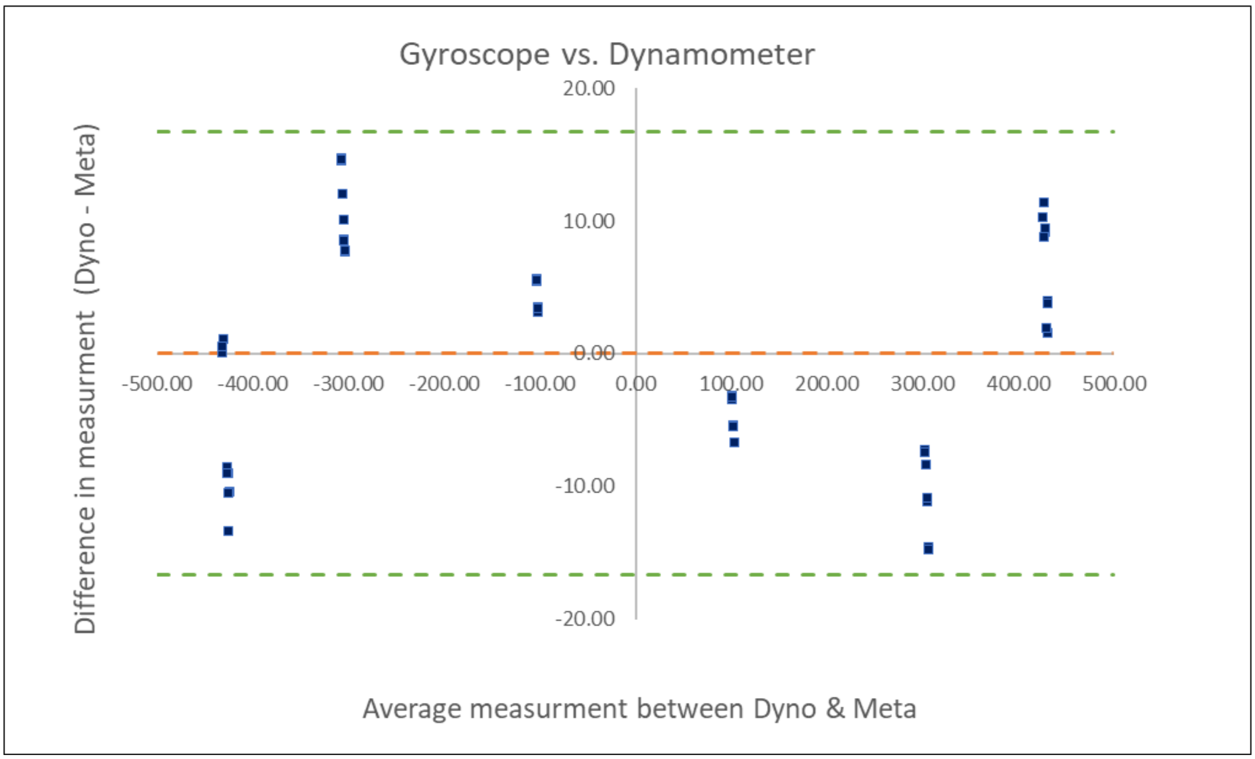

Figure 8. Difference in measurement against average measurement between dynamometer and MetaMotion gyroscope.

CHAPTER IV

MOTION CAPTURE VALIDATION METHODS

Participants

Four subjects participated in this study; two males and two females. Inclusion requirements to participate in this study were persons between the age of 10-55 years old and able to walk independently. Since this study aims to validate sensors versus performance trends, a small study group was deemed sufficient.

Sensor Placement

Now that the known errors of the MetaMotion sensor and its individual components are understood, the second half of this study looks at the validity of using these sensors out in the field to study biomechanics. As mentioned at the beginning of this study, a common practice to study biomechanics is through marker-based motion capture, which can be very limiting. This section of the study will validate the MetaMotion sensors against Vicon motion capture data by measuring knee angle during gait.

The orientation and movements between two MetaMotion sensors were used to calculate the knee angle of the subject's leg. One sensor is located on the thigh to represent the thigh orientation and the other sensor is located on the shank to represent the shank orientation (Figure 3). Transforming the sensor orientation to the body segment orientation is described later in this paper. It is also important to note that only one of the sensors was validated during the dynamometer validation. Even though individual sensors will exhibit unique bias, it is assumed that sensors made by the same manufacturer will offer similar results in terms of validation.

Like in the dynamometer validation, the sensors are first calibrated using the sensor box to calculate the axis offset that is used during data processing. This method for calibrating the sensors is completed on each power cycle of the sensors, therefore each subject will have their unique sensor bias associated with their files. Once calibration files of all three axes were recorded, the sensors were ready to be placed on the subject. Double sided tape was used to place both sensors on the subject’s right leg. Both sensors are placed in the same orientation on the outside of the thigh and the shank as shown in Figure 9. Optimal sensor placement was determined by previous work (Niswander et al., 2020). While it was not necessary to place both sensors in the same orientation for all subjects, since each sensor to segment orientation is unique, it is easier to understand the initial orientation of the sensors across data collection during post processing.

Figure 9. MetaMotion sensor placement on thigh and shank.

Using double sided tape, Vicon reflective markers are placed on the subject to allow for motion capture of the right leg. Anatomical markers are placed on the medial and lateral malleolus, medial and lateral femoral epicondyles and left and right greater trochanters. Marker clusters (tracking markers) were placed over each MetaMotion sensor, one on the thigh and the other on the shank. Marker clusters are secured with Velcro and tape, which also secures the MetaMotion sensors. Marker placement is shown in Figure 10.

Figure 10. Marker placement guide. Note: MetaMotion sensors are under each marker plate.

Finally, the Vicon system is calibrated to the capture volume and the ground plane is set.

Sensor to Segment Alignment

In “traditional” motion capture or in this case for Vicon, determining the orientation of a body segment in space is calculated from three non-collinear points along the segment. One marker is placed at the proximal point of the segment and the other is placed at the distal point of the segment. The third marker provides the depth and ultimately the orientation of the segment in space. This concept is only useful in marker-based motion capture.

When using one point or one sensor, accurate methods for determining sensor to segment orientation have been studied. As mentioned above, the sensor on the thigh represented the thigh orientation and the same concept applies to the shank and its sensor. In this study, the methods used for determining the orientation of the sensor with respect to the orientation of the body segment are based on two assumptions: 1) The thigh and shank vertical axes align with gravity when the subject is in the static pose (described below), and 2) The knee and hip joints can act as hinge joints during functional movements, restricting movement in the ab/adduction and internal/external rotation planes.

The subject is asked to hold a static pose where they stand upright, with their knees straight and feet hip width apart. A static trial is recorded for roughly 5 seconds. The static trial is used for two purposes. One purpose is for defining the segments in the Vicon system using its reflective markers. The other purpose is for determining the vertical axis of the thigh and shank segments through calculating the gravity vector of the sensor during the static pose (Assumption #1).

Next the subject is asked to perform functional rotational movements to determine the medial lateral axis of each segment. The following functional movements were only required for the MetaMotion sensors to establish orientation. Vicon Nexus can determine segment orientations from the static trials recorded prior to this stage. All functional movement trials were recorded at 100Hz. For the first movement, the subject is asked to hinge at the knee by lifting their thigh parallel to the ground, hold their thigh in place and kick their shank back and forth 5 times (extending and flexing the knee joint). Rotational velocities (gyroscope data) are recorded on the shank sensor. For the second movement, the subject is asked to do a similar movement but this time hinging at the hip while keeping the knee straight. Like the first movement, they swing their leg back and forth 5 times (extending and flexing at the hip joint). Rotational velocities (gyroscope data) are recorded on the thigh sensor. For both movements the subject is taught to keep the movement along their sagittal plane (flexion/extension) for the duration of the movement (i.e. no ab/adduction or internal/external rotations). These movements rotate each sensor about their mediolateral axis. The mediolateral axis is calculated by taking the root mean square of the angular rotation of the sensor (Assumption #2).

Once the vertical and mediolateral axis is determined, the anterior/posterior axis is calculated by simply taking the cross product of the vertical axis and the medial/lateral axis. Calculations are discussed further in this paper.

Dynamic Trials

Following the calibration and sensor alignment protocol, the subject was ready to begin the dynamic trials. To capture gait, the subject was asked to begin at one end of the room and walk at a comfortable pace to a marked ending point at the other end of the room. The subject was instructed to begin once the Vicon system and MetaMotion sensors were recording. At the end of the trial the subject would turn around and make their way back to the starting mark. This was repeated five times for five walking trials. MetaMotion data was recorded at 100Hz and Vicon was recorded at 200Hz for all dynamic trials.

Sensor Data Processing

MetaMotion data is recorded on the iOS MetaMotion app, MetaBase. Within the app different sensor readings and frequencies are configured as shown in Figure 11.

Figure 11. MetaBase iOS application data logging set up.

MetaBase also has the ability to group several sensors together to record the same sensors and frequencies simultaneously. After the data is recorded all sensor files are offloaded from the sensors to the app as a .csv file. Each sensor reading within one MetaMotion (accelerometer, gyroscope, etc.) offloads as a separate file. During the offload of sensor data of one of the subject's trials, the MetaMotion app crashed and all sensor data was lost. Therefore, only three participants' datasets were usable for validation.

Once all sensor files were offloaded from the sensors, the files were first processed for sensor bias and timing offsets. Calibration files obtained for each subject were used to correct all of the data files for sensor bias. Equations 1 and 2 were used to correct for accelerometer and gyroscope bias. After accounting for sensor bias, the accelerometer and gyroscope sensor files of an individual sensor were manually aligned with one another so that their global time stamps were synchronized. Then, the two sensors, the thigh and shank sensors were time synchronized for each dynamic trial.

After all files were corrected and time synchronized, sensor to segment coordinate systems were established. Static trials were averaged to the normal vector to represent the vertical axis of the segment. The root mean square was taken for each functional trial (hip and knee trials) to determine the mediolateral axis of the segment. Finally, taking the cross product of these two vectors provides the anteroposterior axis of the segment. This coordinate system established the segment coordinate system in space.

The accelerometer and gyroscope readings of the dynamics trials are passed through an imu filter in MATLAB. The *imufilter* function in MATLAB returns an indirect Kalman filter for fusion of accelerometer and gyroscope data to estimate device orientation relative to the reference frame. The filter uses a nine-element state vector to track error in the orientation estimate, the gyroscope bias estimate, and the linear acceleration estimate (imufilter). All default parameters were used with the *imufilter*. The output was set to rotation matrices.

The segment coordinate system is premultiplied by the sensor rotation matrices to identify the segment position with respect to the sensor readings. The rotation matrices of the segment's position are represented as Euler angles, ψ, θ, and φ and then converted to degrees. Both the shank and thigh sensors are processed individually and then the difference is calculated to represent the knee angle in all three axes. The sagittal plane is used for sensor validation in this study. The MATLAB code used for filtering and processing the IMU data can be found in Appendix E.

CHAPTER V

MOTION CAPTURE VALIDATION RESULTS

To determine the experimental error in the MetaMotion sensors when compared to Vicon, the two datasets were synced and cropped similarly to the dynamometer analysis using the MATLAB function *xcorr*. Figure 12 displays a walking trial, plotting the sagittal flexion/extension knee angles.

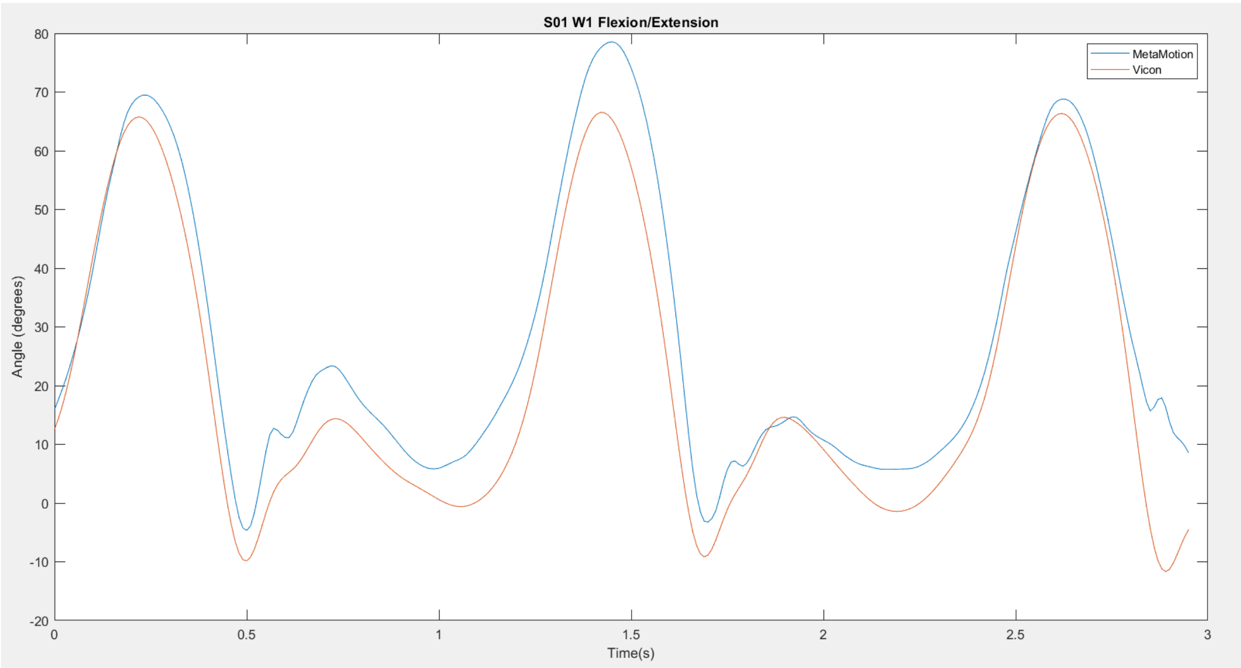

Figure 12. Sagittal plane flexion/extension of walking trial.

While the MetaMotion seems to track the movement path relatively well, there are clear differences between the measured knee flexion and extension angles when compared to Vicon.

Looking at the angles reported from Vicon in Figure 12, consistent knee angles are measured across the three steps. Alternatively, the angles reported by the MetaMotion sensors show inconsistencies with each stride. This behavior appeared in the majority of the walking trials which may have resulted from suspected gyroscope drift or accelerometer decay throughout each trial.

Once the walking trials were processed, minimum and maximum knee angles (maximum extension and maximum flexion) were reported for each trial in Table 4.

Table 4. Peak knee extension and flexion values measured by Vicon and MetaMotion.

Subject 1			
Knee Extension		*Knee Flexion*	
Vicon	**Meta**	**Vicon**	**Meta**
-11.67	-4.66	66.54	78.56
-11.82	-21.80	66.39	87.09
-11.42	-3.95	67.91	91.48
-10.99	-7.10	67.89	80.95
-11.09	-6.22	71.03	88.52
Subject 2			
-4.93	-4.41	84.97	66.47
-1.20	1.51	69.37	64.52
1.48	-8.42	70.51	56.86
-2.35	-30.01	70.01	56.97
1.95	1.01	70.10	63.79
Subject 3			
-8.60	-16.58	63.55	48.26
-9.52	-15.15	64.56	44.79
-8.58	-16.63	63.43	74.76

Like the dynamometer validation, the MetaMotion sensors are validated against the Vicon system using the same statistical analysis of agreement. Knee angles, mean difference ($\underline{d}$), the standard deviation of the differences in values (s) and the lower and upper “limits of agreement” are reported in Table 5 for each subject.

Table 5. Limits of Agreement between Vicon and MetaMotion for joint angle.

Mean Difference	1.42
Standard Deviation	12.92
Limits of Agreement	{-24.42, 27.26}

This analysis suggests that the MetaMotion would measure joint angles around 24.42 degrees above and/or 27.26 degrees below the true measurement. Figure 13 plots the difference in mean for each subject at their max knee extension and flexion angles between the Vicon and MetaMotion.

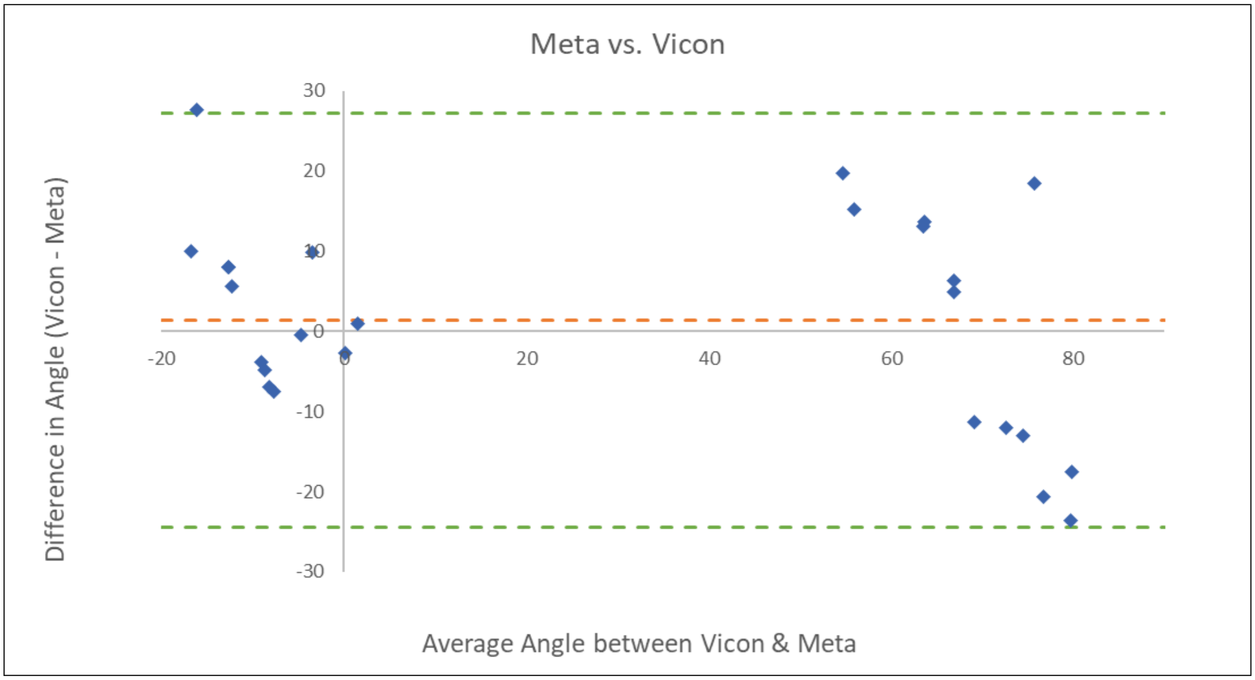

Figure 13. Difference in measurement against average measurement between Vicon and MetaMotion.

Figure 14 shows an example of a trial where the MetaMotion tracked closely to the Vicon measurements or where the mean difference fell closely on the orange line (Figure 13). Conversely, Figure 15 represents a trial where the differences plot closer to the green lines (Figure 13) and the MetaMotion tracked poorly compared to Vicon.

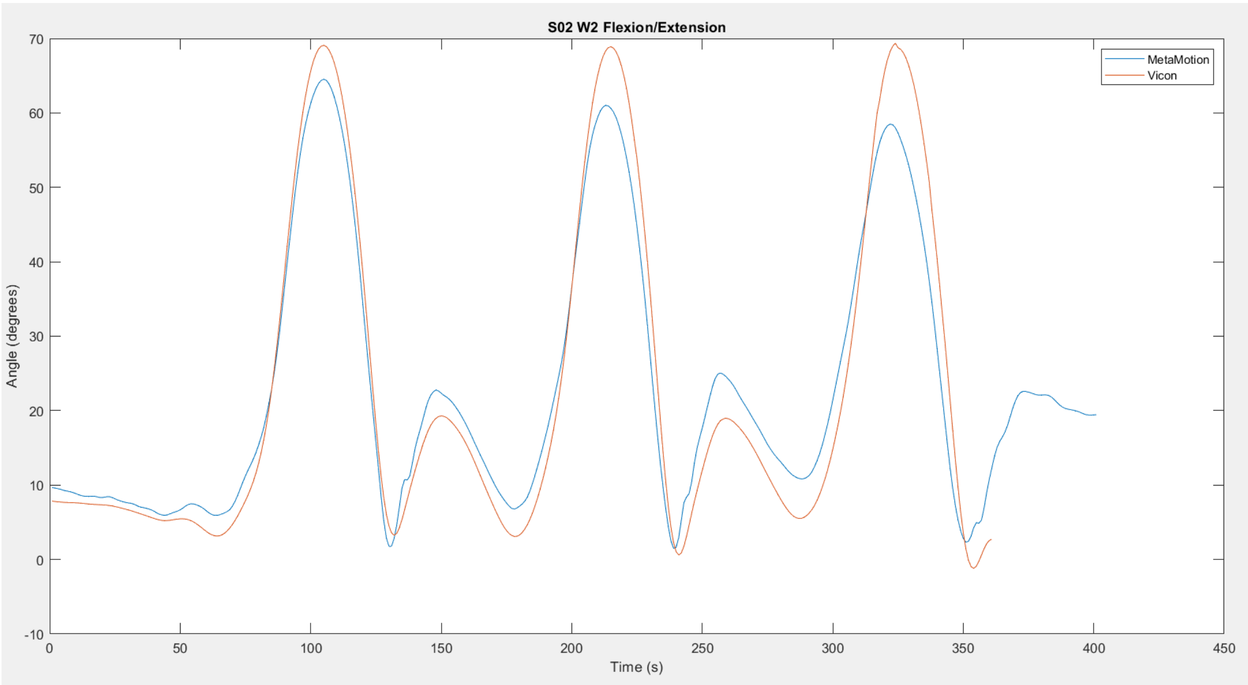

Figure 14. Sample of “good” tracking by MetaMotion. Subject 2, Trial 2.

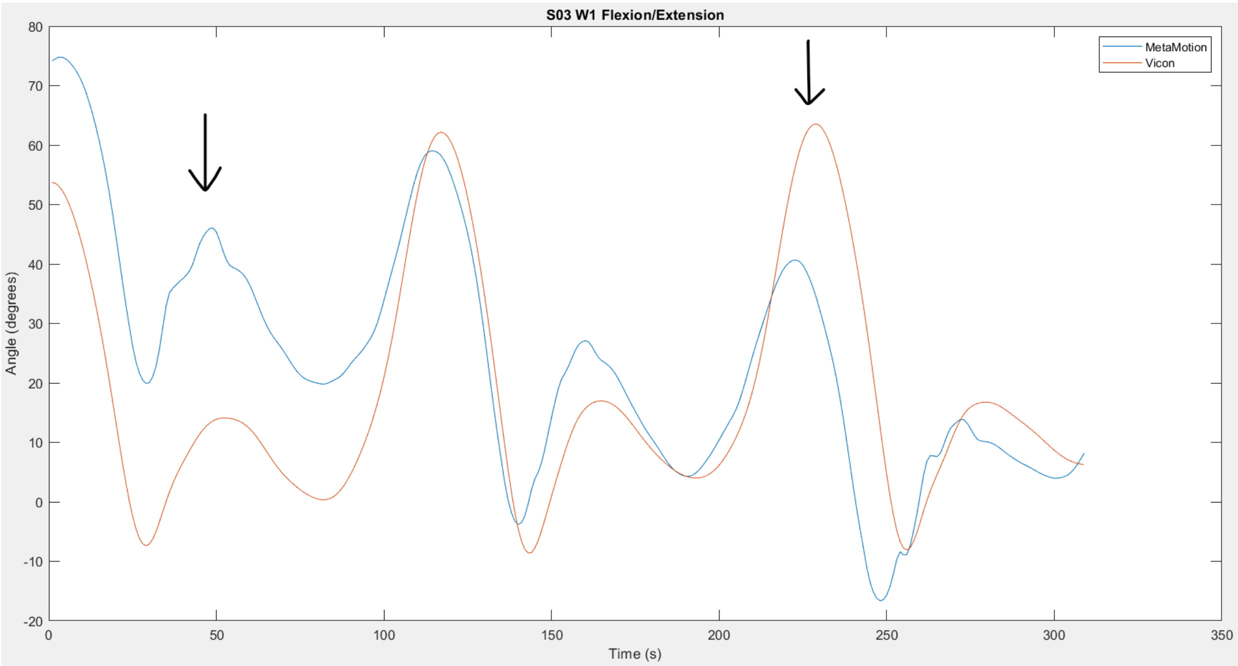

Figure 15. Sample of “poor” tracking by MetaMotion. Subject 3, Trial 1.

CHAPTER VI

DISCUSSION

Overview of Findings

Before assessing the validity of the MetaMotion sensors for biomechanical research applications, the individual components of the IMU should be evaluated. From the dynamometer testing, the accelerometer and gyroscope components of the IMU were assessed against the dynamometer position and angular velocity, respectively. Comparing the accelerometer and the gyroscope, the assessment of agreement would imply the gyroscope component performed at a higher level of agreement with the dynamometer when compared to the accelerometer. The statistical analysis revealed that the MetaMotion measurements would fall between 18.67 degrees above or 8.39 degrees below the dynamometer or true orientation. This may be due to the orientation calculation performed on the accelerometer. Only one axis was used to calculate orientation of the accelerometer, where error increases as the arccos approaches zero. Adding another axis or two to this conversion would likely improve the error seen in the accelerometer as the rotation angle approaches 0 degrees. Accelerometer behavior was consistent across the three speed settings and all three axes. In contrast, the behavior of the gyroscope component changed across the three speeds. The dynamometer had the highest level of agreement at the slowest speed, 100 deg/s, and became less reliable as it sped up. The gyroscope would measure over the true measurement at 100 deg/s and 300 deg/s. As it approaches 500 deg/s it measures less than the true angular velocity. MetaMotion reports its sensors can measure rotations up to 2000 deg/s so it would be interesting to understand the trend of error as speeds neared 2000 deg/s. Unfortunately, in this study the dynamometer was limited to 500 deg/s. The difference in measurements across the three axes was negligible.

While both individual components of the accelerometer and gyroscope showed some disagreement against the dynamometer, it is worth accessing the IMU as one unit in a biomechanical application. The walking trials provide a real world look at MetaMotion capabilities. Since the participant is performing a cyclical task, similar to the motion seen on the dynamometer, it can be expected that the accelerometer and gyroscope components perform similarly to as they did on the dynamometer. However, the method of analysis is different in the walking application versus the dynamometer because the IMU unit is measured using combined values produced by the accelerometer and the gyroscope measurements. Unlike the dynamometer evaluation, sensor fusion is used to predict and correct for sensor error throughout the movement. Nonetheless, the same statistical agreement assessment provides guidance to what can be expected when the MetaMotion sensors are used in the field.

The MetaMotion confidence interval suggested that the sensors will measure 24.42 degrees above and 27.26 degrees below the true joint angle during gait. This range is likely larger than what researchers would accept in this field. Knee angle along the sagittal plane during gait is often a larger movement which could allow for larger errors such as those calculated in this study. Small rotations as seen in ab/adduction or internal and external rotation during gait would require much smaller margins of error to be acceptable. Smaller "limits of agreement" are desired to validate the MetaMotion sensors as accurate measurement tools for biomechanical application, therefore further analysis may be required before the MetaMotion sensors in the field. The sensors proved to follow the movements of the dynamometer and Vicon even when their values did not align exactly. The MetaMotion sensors may be an acceptable tool when looking at relative motion in space or across movement patterns.

Research Limitations

Limitations were found in the MetaMotion sensor as well as the methods presented in this study. There are a few drawbacks to the MetaMotion app and the recording/offloading process that impacted data collection and would likely impact future studies. For one, the sensor readings within a single MetaMotion session do not synchronize (i.e., the data collection did not start and stop simultaneously when data from more than one sensor was collected). During the post processing phase, each set of sensor readings, accelerometer files and gyroscopic files needed to be time synchronized individually. In addition, sensors recorded as a group also do not synchronize, requiring another set of individual time syncing all sensors within the system. The global starting time would be established and the rest of the files would need to be cropped to start at the same starting time. In some cases, the time intervals were off and would require interpolation of the entire file. Another limitation of the MetaMotion would include the time it takes to offload the data increases exponentially with the time of data recordings. A 30-minute data collection session would take upwards of 45-minutes to offload. As mentioned earlier, all sensor data of one subject was lost due to the app crashing during an offload. Following this mishap, data recordings were shortened and sensor data was offloaded after each individual trial, about 1-minute data collection sessions. As a result, files were processed (including time syncing and bias corrections) for each trial, for each set of sensor readings. Data collection became very tedious and the participants had to wait between trials while the sensors were offloading the last trial.

There are several areas in this study where common sensor errors such as drift, noise and bias may cause errors or offsets in the reported measurements. While steps were taken to mitigate these errors, large "limits of agreement" suggest further steps should be taken before using MetaMotion sensors for more precise biomechanical measurements. For one, the bias calculated from the dynamometer trials can be assessed to predict the bias seen in similar biomechanical movements. This study showed gyroscope bias changes at varying speeds. Therefore, if kinematic data is evaluated, sensor bias could be adjusted based on different speeds of the movements. Using more unique sensor bias in place of null bias would likely reduce error due to sensor bias. In addition to bias, measuring and understanding gyroscopic drift and accelerometer decay of the sensor over time, specifically with abrupt motions, could aid in reducing sensor error. Finally, different filtering techniques to reduce sensor noise, depending on the configuration of the sensor could be evaluated.

The sensor to segment alignment also brought limitations to this study. Assumptions were made about the knee joint and the body alignment with Earth's gravity that may have caused offsets to the measurements. The alignment method could be assessed for accuracy in comparison to the body alignment built in Vicon to truly understand the errors of the MetaMotion sensors. Figure X is a possible example where the sensor to segment alignment introduced additional error to this study. All bodies are shaped differently and do not all follow the assumptions made here. For example, a person with wider hips would present a greater angle from their hip to their foot when standing straight up when compared to a person with narrow hips. Therefore, the vertical axis would be off and impact the entire system. Likewise, the functional trials require accurate performance by the subject which can only be controlled to such extent.

While the analysis in this study is capable of evaluating all three planes to include internal/external rotations and ab/adduction of the knee joint, this study is limited to flexion/extension rotations. It would be interesting to see how the MetaMotion sensors behave with my smaller rotations to see if the margin of error increases or decreases with the size of the movement or rotation.

Lastly, the agreement assessment assumed the data to be normally distributed. While the design of this study would suggest the differences found between the two measuring systems would be normally distributed, additional post analysis and a larger sample size would build confidence in this statement.

Suggestions for Future Research

As the use of IMUs becomes more popular in the biomechanical testing environment, there is more work to be done in validating commercial units such as the MetaMotion. Regarding application, movements other than gait should be studied including non-repetitive, unpredictable, and free-swinging motions. Studying a range of motions from big movements to small rotations would test the limits of these sensors. Different methods of segment to sensor alignment should be validated especially on ball and socket joints when less assumptions are made about the human body. Finally, testing different IMUs or including the built in magnetometer could speak to all the capabilities of IMUs in biomechanical applications. Future research involving the use of IMUs for biomechanical analysis could provide more affordable and realistic approaches in the field of biomechanics.

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APPENDICES

Appendix A. Consent Form

INFORMED CONSENT DOCUMENT

OLD DOMINION UNIVERSITY

PROJECT TITLE: A Database of Kinematics Measured from Wearable Technology during Gait and Jumping Tasks.

INTRODUCTION
The purposes of this form are to give you information that may affect your decision whether to say YES or NO to participation in this research, and to record the consent of those who say YES.

The research on the wearable technology and portable devices during activities of daily living will be conducted in the Neuromechanics Lab.

RESEARCHERS
Dr. Hunter Bennett, a faculty member from Old Dominion University Darden College of Education and Professional Studies in the department of Human Movement Sciences, is the principal investigator for this research.

Dr. Stacie Ringleb, a faculty member from Old Dominion University Darden College of Engineering in the department of Mechanical and Aerospace Engineering, is an investigator for this research.

Lauren Luginsland, a graduate student from Old Dominion University Darden College of Education and Professional Studies in the department of Human Movement Sciences, is an investigator for this research.

Kiara Barrett, a graduate student from Old Dominion University Darden College of Education and Professional Studies in the department of Human Movement Sciences, is an investigator for this research.

Kerri Caruso, a graduate student from Old Dominion University Darden College of Engineering in the department of Mechanical and Aerospace Engineering, is an investigator for this research.

DESCRIPTION OF RESEARCH STUDY
Devices you can wear (called inertial measurement units (IMUs)) have recently become popular in science due to their ease of access and convenient nature. This technology is similar to Apple Watches and FitBit devices that can track change in position and movement. The purpose of our study is to create a database of healthy persons which will be used to develop a baseline for future research. This information may be compared to other populations in the future, providing useful information about body movements. Walking, running, and jumping will be recorded using devices you can wear and a walking mat.

If you choose to participate, you are expected to attend one testing session lasting around an hour and a half. In this session, you will be asked to wear spandex shorts and a tank top. The researchers will apply passive IMUs, small black boxes that record your change in position and movement, to the skin specifically on the upper and lower limbs, torso, and pelvis via transpore tape. Researchers will then place reflective markers on the skin via tape and Velcro wraps to outline anatomical landmarks on the arms, torso, as well as the upper and lower limbs. Once all markers and IMU electrodes are in place, you will then be asked to complete a 5-minute warmup whereby you will walk and run. Following completion of the warmup, you will be asked to walk approximately 10 times at your self-selected speed across an 18-meter walkway. After the completion of walking, you will be asked to run the same fixed distance. We will also utilize a portable ProtoKinetics walking mat which rolls out flush on the data collection floor in the same data capture space to obtain standard walking measurements. After walking and running you will be asked to perform 5 maximal vertical jumps.

If you say YES, then your participation will last for an hour and a half at the ODU Neuromechanics lab. Approximately 200 other participants will be participating in this study.

EXCLUSIONARY CRITERIA
To the best of your knowledge, you should not have current musculoskeletal that impairs movement and/or limits your own personal physical activity level engagement. For example, an injury that made you limit your run time or kept you from exercising altogether for more than 1 day. Additionally, you should not participate in this study if you outside of the age range of 8-55, or if you are not able to walk or run without the use of an assistive device (walker, wheelchair, cart). Furthermore, taking medications/drugs that may make you dizzy or make you tired (i.e. cold medications, sleeping medications, muscle relaxants will prevent you from participating in this study. Lastly, you cannot participate in this study if you have a silver allergy, a pacemaker, or any open wounds in the area of sensor placement.

RISKS AND BENEFITS
RISKS: If you decide to participate in this study, then you may face a potential risk of tripping and falling, however the risk is minimal due to the commonplace nature of walking and running. There is no risk of release of confidential information. The researcher mitigated these risks by not connecting any identifiable information with recorded data along with only referring to participants by their assigned code. And, as with any research, there is some possibility that you may be subject to risks that have not yet been identified.

BENEFITS: There are no direct benefits for participating in this study.

COSTS AND PAYMENTS
The researchers want your decision about participating in this study to be voluntary. There is no financial compensation for your completion of this study.

NEW INFORMATION
If the researchers find new information during this study that would reasonably change your decision about participating, then they will give it to you.

CONFIDENTIALITY
The researchers will take reasonable steps to keep private information, such as questionnaires and medical history, are confidential. Your identifiable information (only here on this form) will never be connected with your recorded data. Your data will be recorded based only on a number/code assigned to you. This number assigned will be used as your subject ID when collecting and storing data within the computer. The questionnaires given to you will be confidential; you will be asked to not write your name on the questionnaires (only the number/code assigned to you). Any computers used to capture data will be password protected and data files will be labeled only using the participant code. The results of this study may be used in reports, presentations, and publications; but the researcher cannot identify you. Your data may be used in future studies within a healthy control dataset to compare with other populations. Of course, your records may be subpoenaed by court order or inspected by government bodies with oversight authority.

WITHDRAWAL PRIVILEGE
It is OK for you to say NO. Even if you say YES now, you are free to say NO later, and walk away or withdraw from the study -- at any time. Your decision will not affect your relationship with Old Dominion University, or otherwise cause a loss of benefits to which you might otherwise be entitled.

COMPENSATION FOR ILLNESS AND INJURY
If you say YES, then your consent in this document does not waive any of your legal rights. However, in the event of injury arising from this study, neither Old Dominion University nor the researchers are able to give you any money, insurance coverage, free medical care, or any other compensation for such injury. In the event that you suffer injury as a result of participation in any research project, you may contact the responsible principal investigator, Dr. Hunter Bennett at 757-683-4387, Dr. Tancy Vandecar-Burdin the current IRB chair at 757-683-3802 at Old Dominion University, or the Old Dominion University Office of Research at 757-683-3460 who will be glad to review the matter with you.

VOLUNTARY CONSENT
By signing this form, you are saying several things. You are saying that you have read this form or have had it read to you, that you are satisfied that you understand this form, the research study, and its risks and benefits. The researchers should have answered any questions you may have had about the research. If you have any questions later on, then the researchers should be able to answer them:
Dr. Hunter Bennett: 757-683-4387

If at any time you feel pressured to participate, or if you have any questions about your rights or this form, then you should call Dr. Tancy Vandecar-Burdin, the current IRB chair, at 757-683-3802, or the Old Dominion University Office of Research, at 757-683-3460.

And importantly, by signing below, you are telling the researcher YES, that you agree to participate in this study. The researcher should give you a copy of this form for your records.

Subject's Printed Name & Signature	Date

<u>INVESTIGATOR'S STATEMENT</u>

I certify that I have explained to this subject the nature and purpose of this research, including benefits, risks, costs, and any experimental procedures. I have described the rights and protections afforded to human subjects and have done nothing to pressure, coerce, or falsely entice this subject into participating. I am aware of my obligations under state and federal laws and promise compliance. I have answered the subject's questions and have encouraged him/her to ask additional questions at any time during the course of this study. I have witnessed the above signature(s) on this consent form.

Investigator's Printed Name & Signature	**Date**

Appendix B. Medical Questionnaire

Medical History & Physical Activity Questionnaire

Please answer the following questions to the best of your ability:

Biological Sex:
☐Male ☐Female

Race/ethnicity *(please check all that apply)*:
☐American Indian/Alaska Native
☐Asian
☐Native Hawaiian or other Pacific Islander
☐Hispanic or Latino
☐Black or African American
☐White
☐Prefer not to answer

Which leg would you use to kick a ball?
☐Right ☐Left

To be completed by investigator:

Age:________ yr Height: ________ m Mass: ________ kg

Medical History Questionnaire
For your safety, a list of conditions that would make you unable to participate in this study has been prepared. Please read this list carefully and consider whether any of the conditions apply to you. If any of these conditions are true for you, you will not be able to participate in this study. For each condition, please indicate "yes" or "no" if this is true or not for you.

☐Yes ☐No Are you currently physically active at a moderate level for at least 30 minutes/day, at least 3 days of the week?

☐Yes ☐No Do you have a medical condition that may impair your balance performance (i.e. concussion, neurological impairments, etc)?

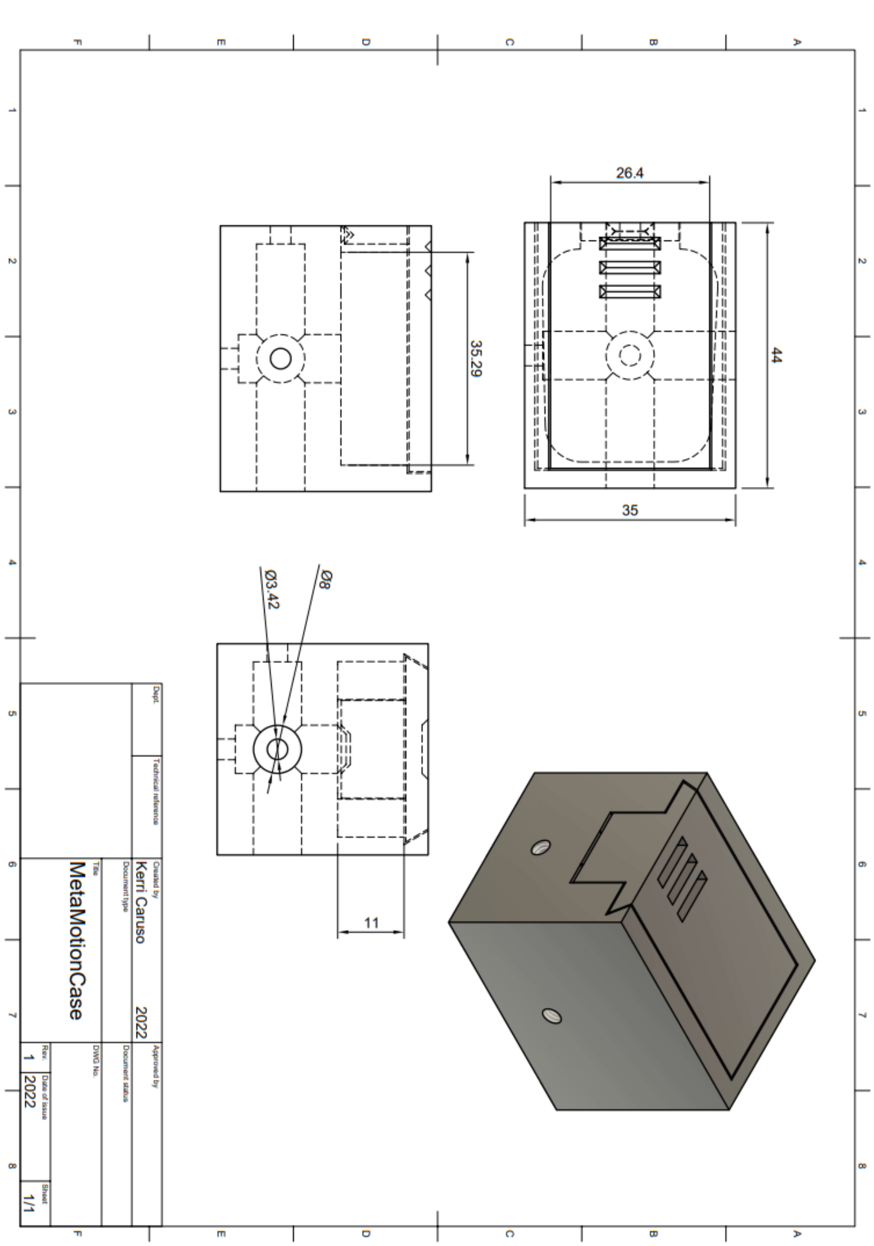
☐Yes ☐No Are you taking medications/drugs that may make you dizzy or make you tired (i.e. cold medications, sleeping medications, muscle relaxants)?

☐Yes ☐No Have you ever had a lower extremity injury that caused you to decrease the amount of physical activity you undertake? If yes, please complete the following:
☐Yes ☐No Hip injury(ies)
If yes, approximately how many injuries?_________________________
☐Yes ☐No Knee injury(ies)
If yes, approximately how many injuries? _________________________
☐Yes ☐No Ankle/foot injury(ies)
If yes, approximately how many injuries?

☐Yes ☐No Are you currently unable to perform your usual amount of physical activity due to pain/injury?

☐Yes ☐No Are you able to ambulate independently (no assistive devices i.e. walker/wheelchair)?

Appendix C. Sensor Case CAD Drawing.



Appendix D. MATLAB code for IMU against Dynamometer.

```
%This code validates the gyroscope and accelerometer of the MetaMotion
%compared to the Dynamometer. The axis that is rotated about is validated
%against rotational velocity (deg/s) while the vertical axis (when sensor is at starting posiiton)
is validated
%against position (angle). Prior to running this code, crop the run and adjust for sensor bias in
excel.

clear
clc

%Read MetaMotion files.

accData =
readtable('Z_Axis_Meta_Accelerometer.xlsx','Sheet','100_1','ReadVariableNames',false);
%change with trials.
accReadings = accData{:,8};
gyroData =
readtable('Z_Axis_Meta_Gyroscope.xlsx','Sheet','100_1','ReadVariableNames',false); %change
with trials.
gyroReadings = gyroData{:,8};

%Convert g to degrees.

accReadings = acosd(accReadings/1);

fs=100; %Hz
fpass=0.6;

metaPos = lowpass(accReadings,fpass,fs);
metaVel = lowpass(gyroReadings,fpass,fs);

%Read Dynamometer files

dynoData = readtable('Z_Axis_Dynamometer.xlsx','Sheet','100_1','ReadVariableNames',false);
%change with trials.
dynoPos = dynoData{:,2};
dynoVel = dynoData{:,4};

[c1,lags1] = xcorr(dynoPos,metaPos);
c1 = c1/max(c1);
[m1,t1] = max(c1);
t1 = lags1(t1);
```

```
dynoPos = dynoPos(t1:end);

n1=min(numel(dynoPos),numel(metaPos));
dynoPos=dynoPos(1:n1);
metaPos=metaPos(1:n1);

metaPos = abs(metaPos);

[c2,lags2] = xcorr(dynoVel,metaVel);
c2 = c2/max(c2);
[m2,t2] = max(c2);
t2 = lags2(t2);

dynoVel = dynoVel(t2:end);

n2=min(numel(dynoVel),numel(metaVel));
dynoVel=dynoVel(1:n2);
metaVel=metaVel(1:n2);

timeA = (0:size(metaPos,1)-1)/100;
timeG = (0:size(metaVel,1)-1)/100;

figure
subplot(2,1,1)
plot(timeA,metaPos)
hold on
plot(timeA,dynoPos)
hold off
xlabel('Time(s)')
ylabel('Angle (degrees)')
legend('MetaMotion', 'Dynamometer')
title('100 deg/s')

subplot(2,1,2)
plot(timeG,metaVel)
hold on
plot(timeG,dynoVel)
hold off
xlabel('Time(s)')
ylabel('Angular Velocity (deg/s)')
legend('MetaMotion', 'Dynamometer')
title('100 deg/s')

metaPosMin = min(metaPos);
dynoPosMin = min(dynoPos);
metaVelMin = min(metaVel);
```

```
dynoVelMin = min(dynoVel);

metaPosMax = max(metaPos);
dynoPosMax = max(dynoPos);
metaVelMax = max(metaVel);
dynoVelMax = max(dynoVel);
```

Appendix E. MATLAB code for IMU against Vicon.

```
%This code calculates the knee joint angle between two IMU sensors that provide acceleration
and gyroscopic data. All raw data was adjusted for sensor bias prior to running this code.

clear
clc

%Establish vertical axis of segment. Gravity vector during static trial.

shankStatic = readtable('Shank_Vertical_S01.xlsx'); %change file with subject
shankStatic = shankStatic{:,[3,4,5]};

shankAvgStatic = mean(shankStatic);
shankGrav = shankAvgStatic/norm(shankAvgStatic);

%Establish medial-lateral axis of segment. Root mean square of functional trial.

kneeFunc = readtable('Shank_MidLat_S01.xlsx'); %change file with subject
kneeFunc = kneeFunc{:,[3,4,5]};

shankFunc = rms(kneeFunc);
shankMid = shankFunc/norm(shankFunc);

%Establish ant-post axis for segment. Cross product of gravity and medial-lateral vectors.

shankAnt = cross(shankGrav,shankMid);

shankCoord = [shankAnt; shankMid; shankGrav];

%IMU filter.

fuse = imufilter('SampleRate',100,'OrientationFormat','Rotation matrix', 'ReferenceFrame',
'NED');

%Load accel and gyro data and pass through IMU filter

shankAccel = readtable('W1_S01.xlsx','Sheet','ShankAccel','ReadVariableNames',false);
%change file with subject/trial
shankAccel = shankAccel{:,[3,4,5]};
shankAccel = shankAccel.*9.81; %convert g to m/s^2

shankGyro = readtable('W1_S01.xlsx','Sheet','ShankGyro','ReadVariableNames',false);
%change file with subject/trial
shankGyro = shankGyro{:,[3,4,5]};
```

```
shankGyro = shankGyro.*(pi/180); %convert deg/sec to rad/sec

[shankRot,shankAngVel] = fuse(shankAccel,shankGyro);

%Premultiply segment coordinate systems by rotation matrix.

for i=1:size(shankAccel)

    shankPos(:,:,i)=shankCoord*shankRot(:,:,i);

end

%Convert rotation matrix to angles.

shankAng = rotm2eul(shankPos);
shankAng = rad2deg(shankAng);

timeMeta = (0:size(shankAccel,1)-1)/100;

%Repeat steps for second sensors.

thighStatic = readtable('Thigh_Vertical_S01.xlsx');
thighStatic = thighStatic{:,[3,4,5]};

thighAvgStatic = mean(thighStatic);
thighGrav = thighAvgStatic/norm(thighAvgStatic);

hipFunc = readtable('Thigh_MidLat_S01.xlsx');
hipFunc = hipFunc{:,[3,4,5]};

thighFunc = rms(hipFunc);
thighMid = thighFunc/norm(thighFunc);

thighAnt = cross(thighGrav,thighMid);

thighCoord = [thighAnt; thighMid; thighGrav];


thighAccel = readtable('W1_S01.xlsx','Sheet','ThighAccel','ReadVariableNames',false);
thighAccel = thighAccel{:,[3,4,5]};
thighAccel = thighAccel.*9.81; %convert g to m/s^2

thighGyro = readtable('W1_S01.xlsx','Sheet','ThighGyro','ReadVariableNames',false);
thighGyro = thighGyro{:,[3,4,5]};
thighGyro = thighGyro.*(pi/180); %convert deg/sec to rad/sec
```

```
[thighRot,thighAngVel] = fuse(thighAccel,thighGyro);

for i=1:size(thighAccel)

    thighPos(:,:,i)=thighCoord*thighRot(:,:,i);

end

thighAng = rotm2eul(thighPos);
thighAng = rad2deg(thighAng);

%Calculate knee angle in sagittal plane.

kneeAngle = thighAng - shankAng;
kneeAngle = kneeAngle(:,2);

%Vicon Data
viconData = readtable('W1_S01_Vicon.xlsx','ReadVariableNames',false); %Change with trial
viconData = -table2array(viconData);
viconData = viconData(:,1);
timeVic = (0:size(viconData,1)-1)/200;

viconData = downsample(viconData,2); %200hz to 100hz

[c,lags] = xcorr(viconData,kneeAngle);
c = c/max(c);
[m,t] = max(c);
t = lags(t);

viconData = viconData(t:end);

n=min(numel(kneeAngle),numel(viconData));
kneeAngle=kneeAngle(1:n);
viconData=viconData(1:n);

figure
plot(kneeAngle)
hold on
plot(viconData)
hold off

metaMin = min(kneeAngle);
vicMin = min(viconData);
metaMax = max(kneeAngle);
vicMax = max(viconData);
```

Appendix F. Old Dominion University IRB Approval Form.

OLD DOMINION UNIVERSITY

OFFICE OF THE VICE PRESIDENT FOR RESEARCH

aalac INTERNATIONAL PROUDLY, AN AAALAC ACCREDITED PROGRAM

Physical Address
4111 Monarch Way, Suite 203
Norfolk, Virginia 23508
Mailing Address
Office of Research
1 Old Dominion University
Norfolk, Virginia 23529
Phone(757) 683-3460
Fax(757) 683-5902

DATE:	August 29, 2022
TO:	Hunter Bennett, PhD
FROM:	Old Dominion University Institutional Review Board
PROJECT TITLE:	[1937417-2] A Database of Wearable Technology and Portable Devices Kinematics during gait and jumping tasks
REFERENCE #:	22-111
SUBMISSION TYPE:	New Project
ACTION:	APPROVED
APPROVAL DATE:	August 29, 2022
EXPIRATION DATE:	July 21, 2023
REVIEW TYPE:	Full Committee Review

Thank you for your submission of New Project materials for this project. The Old Dominion University Institutional Review Board has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a project design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received Full Committee Review based on the applicable federal regulation.

Please remember that informed consent is a process beginning with a description of the project and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the project via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document.

Please note that any revision to previously approved materials must be approved by this office prior to initiation. Please use the appropriate revision forms for this procedure.

All UNANTICIPATED PROBLEMS involving risks to subjects or others (UPIRSOs) and SERIOUS and UNEXPECTED adverse events must be reported promptly to this committee. Please use the appropriate reporting forms for this procedure. All FDA and sponsor reporting requirements should also be followed.

All NON-COMPLIANCE issues or COMPLAINTS regarding this project must be reported promptly to this committee.

This project has been determined to be a MINIMAL RISK project. Based on the risks, this project requires continuing review by this committee on an annual basis. Please use the appropriate forms for this procedure. Your documentation for continuing review must be received with sufficient time for review and continued approval before the expiration date of July 21, 2023.

Please note that all research records must be retained for a minimum of three years after the completion of the project.

If you have any questions, please contact Adam Rubenstein at 757-683-3686 or arubenst@odu.edu. Please include your project title and reference number in all correspondence with this committee.

This letter has been electronically signed in accordance with all applicable regulations, and a copy is retained within Old Dominion University Institutional Review Board's records.

VITA

Kerri Caruso is a Philadelphia native who graduated from the Downingtown STEM Academy in 2015. After high school, Kerri moved to Norfolk, VA where she attended Old Dominion University to study mechanical engineering and play on the women's lacrosse team. She earned her Bachelor of Science in Mechanical Engineering with a minor in Biomedical Engineering in 2019.

When Kerri began her graduate degree in biomedical engineering, she took her fifth year of eligibility with the women's lacrosse team. After a global pandemic canceled NCAA seasons, Kerri moved to Fort Rucker, AL and worked as a biomedical research engineer at the U.S. Army Aeromedical Research Laboratory. She spent nearly two years developing and testing research protocols that focused on improving patient health outcomes and increasing medical provider performance during medical evacuation transport. While in Alabama, Kerri also trained and earned her pilot license. Kerri currently works outside of Kansas City developing and testing avionics to improve the safety and capabilities of pilots, crews and passengers. While constantly on the move, Kerri commits herself to the community that surrounds her and continues to give back to the ones she has moved away from.