Exploring wearable sensors as an alternative to marker-based motion capture in the pitching delivery

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Background. Technological advancements in Inertial Measurement Unit (IMU) sensors have enabled high precision in the measurement of joint angles and acceleration on human subjects. This has resulted in new devices that reportedly measure joint angles, arm speed, and stresses of baseball players. This study seeks to validate one such sensor, the MotusBASEBALL unit, with a marker-based motion capture laboratory.

Hypothesis. We hypothesize that the joint angle measurements (“Arm Slot” and “Shoulder Rotation”) of the device will be accurate and reliable, but that the “Arm Speed” and “Stress” metrics will not be accurate due to limitations in IMU technology.

Methods. 10 healthy subjects threw 5-7 fastballs followed by 5-7 breaking pitches (slider or curveball) in the motion capture lab. Subjects will be wearing retroreflective markers and the MotusBASEBALL sensor simultaneously.

Results. It was found that the Arm Slot ($P < 0.001$), Shoulder Rotation ($P < 0.001$), and Stress ($P = 0.001$ when compared to elbow torque, $P = 0.002$ when compared to shoulder torque) measurements were all significantly correlated with the results from the motion capture lab. Arm Speed showed significant correlations to shoulder internal rotation speed ($P = 0.001$) and shoulder velocity magnitude ($P = 0.002$). For the entire test population, Arm Slot and Shoulder Rotation measurements were very close to measurements from the motion capture test, averaging 8 degrees less and 9 degrees less respectively. Arm Speed had a much larger difference, averaging 3745 deg/s lower than shoulder internal rotation velocity, and 3891 deg/s less than the shoulder velocity magnitude. The Stress metric was found to be 41 Nm less when compared to elbow torque, and 42 Nm less when compared to shoulder torque. Despite the differences in magnitude, the correlations were extremely strong, indicating that the MotusBASEBALL sensor could be valid for casual use.

Conclusions. This study validates the use of the MotusBASEBALL for future studies that look at the Arm Slot, Shoulder Rotation, Arm Speed, and Stress measurements from the MotusBASEBALL sensor. Excepting elbow extension velocity, all metrics from the MotusBASEBALL unit showed significant correlations to their corresponding metrics from motion capture. While magnitudes differ significantly in the Arm Speed and Stress metrics between MotusBASEBALL and the motion capture lab, the link between the metrics is strong enough to indicate valid casual use. Further research should be done to further investigate the validity and reliability of the Arm Speed metric.

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Abstract

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Introduction

Marker-based motion capture has been shown in research to be suitable in measuring the kinematics and kinetics of a baseball throw (Richards, 1999). The OptiTrack camera system (Natural Motion / OptiTrack; Corvallis, Oregon) used in this study has also been shown in research to be comparable to other high-end motion capture systems (Thewlis et al., 2013).

Inertial Measurement Unit (IMU) sensors have been validated in research for joint angle measurements (Leardini et al., 2014), gait analysis (Kavanagh and Menz, 2008), kinematics of runners (Provot et al., 2017), as well as swimming biomechanics (de Magalhaes et al., 2014). IMU sensors have started to gain popularity in measuring the kinematics of throwers, but validation of such sensors has been limited.

One study used IMU sensors to measure kinematics of youth throwers, but the study focused primarily on pelvis and torso rotation; the sensor attached to the wrist was only used to identify the timing of the acceleration phase of the throwing motion (Grimpampi et al., 2016).

The MotusBASEBALL unit (Motus; New York, NY) is a popular IMU sensor that purports to measure the biomechanics of a thrower's elbow. The only existing validation of the unit comes from Camp et al., 2017, which states that the MotusBASEBALL sensor was evaluated simultaneously with an 8-camera motion capture system. Correlation coefficients (r-values) between measurements with the 2 systems were found to be "good to excellent" for all measurements, though no supplemental data was provided. Following studies have used the MotusBASEBALL unit to look at elbow torque and other parameters in pitchers throwing fastballs and offspeed pitches as well (Makhni et al., 2018)

A case study performed by Motus showed the MotusONE, a multi-unit IMU device, to be comparable to multi-camera motion capture setups, but the study only had one subject, and to our knowledge was not published in any peer reviewed journal.

The purpose of this study is to compare the outputs of the MotusBASEBALL sensor, which are Arm Speed, Arm Slot, Shoulder Rotation, and Stress, against the OptiTrack motion capture system.

Methods

Ten healthy pitchers were selected to participate in the study, nine threw overhead and one threw sidearm and all were right-handed. Participants were provided a verbal explanation of the study and its risks and were asked to read and sign an Informed Consent document before testing. Testing only proceeded once investigators received verbal confirmation and obtained a witnessed legal signature from the athlete.

Hummingbird IRB approved the study and granted ethical approval to carry out the data collection at the author's facilities (Hummingbird IRB #: **2018-10**).

Heights, weights, and ages of the participants was recorded before the beginning of testing. (Table 1)

[Table 1]

Testing Procedure

Athletes were given as much time as necessary to prepare and warm-up to throw off of the pitching mound. Once ready, pitchers were fitted with reflective markers in preparation for the motion capture test. Forty-seven reflective markers were attached bilaterally on the third distal phalanx, lateral and medial malleolus, calcaneus, tibia, lateral and medial femoral epicondyle, femur, anterior and posterior iliac spine, iliac crest, acromial joint, midpoint of the humerus, lateral and medial humeral epicondyle, midpoint of the ulna, radial styloid, ulnar styloid, distal end of index metacarpal, parietal bone, and frontal bone, as well as on the inferior angle of scapula, C7 and T10 vertebrae, the sternal end of the clavicle, and the xiphoid process.

The motion capture system was calibrated using Motive:Body software (Natural Motion / OptiTrack; Corvallis, Oregon) and the ground plane was set; the system typically showed 1mm or less of mean three-dimensional error, and never exceeded 2mm.

The MotusBASEBALL sensor, which is typically applied using a sleeve, was fixed to the athlete along the medial throwing elbow using double sided skin-tape to avoid the sleeve causing interference with any of the markers. (Figure 1)

[Figure 1]

Pitchers then threw 5-7 fastballs, followed by 5-7 offspeed pitches, either a curveball or a slider, with approximately 30-60 seconds of rest in between throws. All pitches were made at a medium effort level. Research has shown that offspeed pitches may result in significant changes to kinetics and kinematics (Escamilla et al., 2017; Fleisig et al., 2006). For this reason athletes were asked to throw their preferred offspeed pitch. Fatigue was assumed to be negligible with such a low pitch count.

Throws were made using a 5-oz. (142g) regulation baseball off the mound to a strike zone target (Oates Specialties, LLC, Huntsville, TX) located above home plate, which was 60’ 6’’ (18.4 m) away. Testing concluded when the investigators were satisfied they had at least five valid motion capture takes of each pitch type for analysis.

For each trial, ball velocity was measured by a Doppler radar gun (Applied Concepts; Stalker Radar, Richardson, Texas). Additionally, for all trials, the three-dimensional motions of the reflective markers were tracked with a multi-camera motion-capture system, sampling at 240 Hz (Natural Motion / Optitrack, Corvallis, Oregon). This motion-capture system contained a mixture of Prime 13 and Prime 13W cameras, totaling 15 cameras. These cameras were placed symmetrically around the capture volume, approximately 8-12 feet from the center of the pitching mound at varying heights. A total of 6 cameras were mounted on a truss system in front of the pitcher to avoid collisions. (Figure 2)

[Figure 2]

In total, 9 kinematic and kinetic values (3 position, 4 velocity, and 2 kinetic) were calculated using personal code based on Fleisig methods (Fleisig et al., 2017) in Visual3D (C-Motion Inc., Germantown MD). Marker position data was filtered using a 20-Hz Butterworth low-pass filter. The mean values for all variables were calculated for each participant based upon their 5 best throws (Escamilla et al., 1998).

Three position values were found at ball release (BR): trunk lateral tilt, shoulder abduction, and maximum shoulder external rotation. Measurements were taken as their local joint angles measured in degrees.

The four velocity parameters were taken as the maximum speeds of shoulder internal rotation, shoulder abduction, shoulder horizontal abduction, and elbow angular extension. All velocities were calculated as the rate of change in the joint angle, measured in degrees/second.

The two kinetic values calculated were elbow varus torque and shoulder internal rotation torque, which were measured in Newton meters (Nm).

All MotusBASEBALL data was collected with an iPhone (Apple Inc., Cupertino CA) and the supplied app, which was then manually transferred into labeled spreadsheets for storage and later analysis.

Statistical Analysis

The differences in metrics were analyzed as both a total population of twenty (20) pitches and two separate equal-sized groups controlled for the type of pitch: Fastballs and off-speed pitches. To account for any differences in the scale of magnitude between the motion capture measurements and MotusBASEBALL measurements, the statistical analyses centered on a correlation test based around Pearson's product moment of correlation coefficient and an n-2 number of degrees of freedom. The correlation test was used to test the hypothesis of a linear relationship between the two metrics, as opposed to its common statistical compatriot of a T-test, which would rather test for differences in the means of the two metrics.

In order to compare measurements from the motion capture trial to the MotusBASEBALL metrics, additional calculations were done. Corrections to the metrics were done following Motus's guidelines which were sent to us via email by representatives from Motus; those corrections follow below.

Arm Slot was taken as the sum of the lateral trunk tilt and shoulder abduction at BR. Shoulder Rotation was measured as the maximum amount of shoulder external rotation measured in the global coordinate system. MotusBASEBALL's Arm Speed metric, which was taken from the

MotusTHROW app, was compared to elbow extension velocity and shoulder internal rotation velocity, which are the most common standards for measuring arm speed. Per Motus's recommendation, Arm Speed was also compared to the magnitude of the shoulder angular velocities, that is, the square of of the sum of the squares of shoulder abduction velocity, ω_{Sa}, shoulder horizontal abduction velocity, ω_{Sha}, and shoulder internal rotation velocity, ω_{Sir}. $\sqrt{\omega_{Sa} + \omega_{Sha} + \omega_{Sir}}$.

MotusBASEBALL stress was compared to elbow varus torque and shoulder internal rotation torque, which are the two most commonly addressed kinetic markers in pitching research. All torque metrics were in Nm.

First, the descriptive metrics (means and standard errors of means) for the holistic group and subgroups for all the marker-based biomechanics measurements and MotusBASEBALL measurements were outlined and recorded.

Then these metrics were matched together across paired results (each subject having been recorded on the two separate systems), and had both their Pearson correlation coefficient ρ taken, as well as their p-value, following a Student's T test distribution. The correlation test posits the hypothesis of there being a significant linear association versus the null hypothesis of there being no correlation, or ρ = 0.

Results

The results for the three separate groups are displayed in Tables 2 and 3:

[Table 2]

[Table 3]

As is somewhat intuitive given the nature of the more similar sub-populations, the correlation coefficient covers a higher proportion of variability (R^2) within said smaller groups, while also simultaneously recording higher p-values, due to the smaller sample sizes and subsequent degrees of freedom. Interestingly, the fastball group had more significant p-values for the Arm Speed metrics comparisons and the off-speed group had more significant p-values for the Stress metrics.

Following a default alpha value of 0.05, the fastball group found significant associations between four of the metrics (Arm Slot, Shoulder Rotation, and the second and third Arm Speed metrics), while the off-speed group found significant associations between six metrics (Arm Slot, Shoulder Rotation, the second and third Arm Speed metrics, and both Stress metrics).

Given the small sample size circumstance for these tests, a prudent power analysis on the strength of the correlation was also performed. While a typical low p-value cut-off limits the chances of making a Type I error, or a false positive, a statistical power analysis is performed to limit the chances of making a Type II error, or a false negative (also referred to as beta). The magnitude of the power is (1 - P(Type II error)), and a usual cutoff of 0.80 and greater is paired with the alpha level of 0.05 and lower of a p-values significance test. Table 4 illustrates the computed power values for each subgroup of pitches.

[Table 4]

Reducing the risk of Type I error will lead to increasing the risk of a Type II error, so both our significance and power testing has to be carefully calibrated. Looking at the typical 80% power cut-off with a 5% significance level, the fastball population records robust power for the Arm Slot metric while the off-speed population registers robust power for the Arm Slot and Shoulder Rotation metrics.

Discussion

Arm slot was found to be strongly correlated across all groups, though MotusBASEBALL's arm slot was roughly 6 degrees lower than the results from our motion capture system.

Shoulder rotation was also strongly correlated between the two systems. On average the shoulder rotation measured by MotusBASEBALL was 9 degrees lower than what the motion capture system detected for the total group.

Arm speed from MotusBASEBALL showed strong correlations to both shoulder rotation speed metrics, but no correlation to elbow extension speed. This could be due to the fact that the MotusBASEBALL sensor is placed very close to the elbow joint, so movement of the forearm caused by elbow extension is much less detectable due to the shorter lever arm that it detects rotation from.

The numerical difference between the two systems is fairly substantial. Average MotusBASEBALL arm speed, which was 925 deg/s, was dramatically lower than the measured shoulder internal rotation speeds and magnitude of shoulder rotational velocities, which were 4670 deg/s and 4816 deg/s respectively. Motus defines their arm speed metric as the "resultant angular velocity of the forearm segment," which was not directly calculated for this comparison.

It is also worth noting that the arm speed metric that MotusBASEBALL outputs in the app is different than the metric that is in their web-based portal. Because MotusBASEBALL's arm speed metric in the app would scale linearly to the metric in the portal, it follows that the comparison of motion capture arm speed metrics to the arm speed in the app would still be valid.

Both comparisons to MotusBASEBALL's Stress metric were significant. Both stress measurements (from MotusBASEBALL and from motion capture) were shown to be consistent across the athlete population. Kinetics calculations are heavily dependent on the athlete's height and weight, along with the weight of the ball (Feltner and Dapena, 1986). Motus has stated that their calculation also takes these things into consideration and are part of the inputs required to use the MotusBASEBALL sensor. The fact that those inputs are taken into account for both stress calculations could be part of the reason there is a solid correlation between them.

Because the numerical outputs from the MotusBASEBALL unit are noticeably different from the outputs from marker-based motion capture outputs, which is the gold standard of biomechanical analysis, MotusBASEBALL may best be used for relative comparisons of an athlete. MotusBASEBALL has shown to be consistent when used by the same athlete, which makes it a good tool for noting significant changes to an athlete's mechanics. While the MotusBASEBALL unit cannot replace motion capture, the gold-standard of biomechanical analysis, it has a significant advantage in that it can be used in games and practice situations without serious preparation, while clearly a marker-based biomechanics system cannot for various reasons.

The MotusBASEBALL unit is likely best applied by laypeople, coaches, and those who do not have regular access to a sophisticated motion capture system.

As mentioned previously, we did not use a sleeve to place the sensor unlike what athletes would do if they bought the sensor commercially. It therefore is important for athletes and coaches to maintain the position of the sensor as they throw to maintain accurate readings. As movement of the sleeve from the intended sensor location will likely change the readings.

Further research should be done with a larger sample size to further investigate the Arm Speed metric to find if there is a more significant correlation to a measurement of arm speed from a motion capture test.

Conclusion

This results from this study show that MotusBASEBALL could be a suitable low-cost and partial alternative to performing a full biomechanics capture, particularly for the arm slot, shoulder rotation, and stress metrics. Arm speed was shown to have a weak correlation to the results that were found in the motion capture test. It should be noted that while all metrics from MotusBASEBALL had significant variance in values when compared to the motion capture metrics, the numbers were consistent for each subject and across all groups; Arm Slot averaged 8 degrees less than motion capture, Shoulder Rotation averaged 9 degrees less than motion capture, and Stress averaged 41 and 42 Nm less than motion capture for elbow torque and shoulder torque respectively. These three metrics could reasonably be used in future studies, and for use in monitoring an individual athlete's mechanics from session to session.

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Figure 1

Placement of the motusBASEBALL sensor on the elbow

How we affixed the motusBASEBALL sensor to the arm using adhesive instead of the provided sleeve.

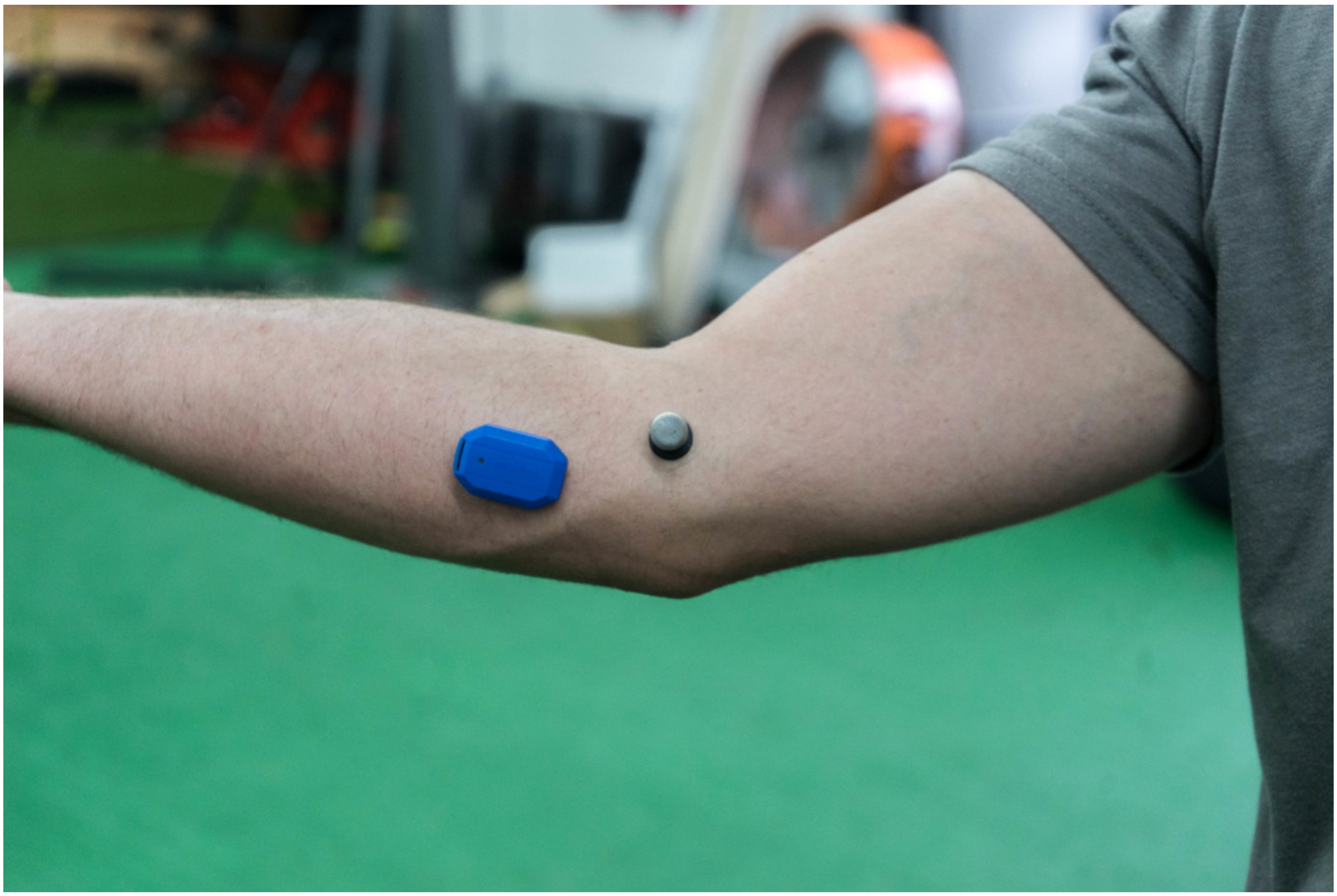

Figure 2

The Motion Capture System

The multi-camera OptiTrack camera system consisting of Prime 13 and Prime 13W cameras, used to evaluate pitcher kinematics and kinetics.

Table 1(on next page)

Age, height, weight, fastball (FB) velocity, and offspeed (OS) velocity of the participants in the study

Biological and performance data on the subjects in the study.

TABLE 1: Age, height, weight, fastball (FB) velocity, and offspeed (OS) velocity of the participants in the study

10 Subjects	Height (in)	Weight (lbs)	FB Velocity (mph)	OS Velocity (mph)
Age: 23.8 ± 4.0	73.3 ± 0.8	206.1 ± 5.5	83.8 ± 3.5	71.0 ± 3.6

Table 2(on next page)

Averages of the Metrics Taken from Motion Capture Analysis Compared with the Corresponding Metrics from MotusBASEBALL

A comparison of the Motion Capture System using high-precision OptiTrack cameras compared with the metrics the motusBASEBALL unit provides.

TABLE 2: Averages of the Metrics Taken from Motion Capture Analysis Compared with the Corresponding Metrics from MotusBASEBALL

Group	All		Fastball		Off-Speed	
Sample Size	20		10		10	
Metric	Motion Capture	MotusBASEBALL	Motion Capture	MotusBASEBALL	Motion Capture	MotusBASEBALL
Arm slot (deg)	62 ± 3	54 ± 8	63 ± 5	53 ± 8	61 ± 5	54 ± 5
Shoulder rotation (deg)	167 ± 2	158 ± 5	167 ± 3	156 ± 5	168 ± 3	157 ± 3
Arm speed - elbow extension speed (deg/s)	2404 ± 38	925 ± 24	2398 ± 49	945 ± 33	2410 ± 61	935 ± 20
Arm speed - shoulder internal rotation speed (deg/s)	4670 ± 130	925 ± 24	4648 ± 178	945 ± 33	4692 ± 199	935 ± 20
Arm speed - shoulder velocity magnitude (deg/s)	4816 ± 120	925 ± 24	4795 ± 167	945 ± 33	4838 ± 181	935 ± 20
Stress - Varus torque (Nm)	106 ± 4	65 ± 3	103 ± 5	62 ± 2	110 ± 6	64 ± 2
Stress - shoulder IR torque (Nm)	107 ± 4	65 ± 3	104 ± 5	62 ± 2	111 ± 6	64 ± 2

Table 3(on next page)

P-Values and Correlation Coefficients (R^2)

Statistical analysis of the comparisons between the Motion Capture System and the motusBASEBALL unit, indicating high correlation.

TABLE 3: P-Values and Correlation Coefficients (R^2)

Group	All		Fastball		Off-Speed	
Sample Size	20		10		10	
Metric	P-Value	R^2	P-Value	R^2	P-Value	R^2
Arm Slot	<0.001*	0.975	<0.001*	0.978	<0.001*	0.974
Shoulder rotation	<0.001*	0.749	0.022*	0.710	0.007*	0.784
Arm speed	0.207	0.295	0.341	0.337	0.413	0.292
Arm speed	0.001*	0.668	0.010*	0.762	0.045*	0.643
Arm speed	0.002*	0.659	0.017*	0.727	0.041*	0.651
Stress	0.001*	0.667	0.077	0.583	0.011*	0.759
Stress	0.002*	0.653	0.094	0.557	0.010*	0.763

* indicates that the metric was found to be statistically significant

Table 4(on next page)

Power Analysis of the Correlations Between Motus Biomechanics Measurements and Marker-Based Biomechanics Measurements

Statistical power of the correlations found between the motusBASEBALL unit and the gold-standard Motion Capture Analysis system.

TABLE 4: Power Analysis of the Correlations Between Motus Biomechanics Measurements and Marker-Based Biomechanics Measurements

Group	Fastball	Off-Speed
Sample Size	10	10
Metric	1-Beta	1-Beta
Arm Slot	0.9999	0.9999
Shoulder rotation	0.6848	0.8260
Arm speed	0.1619	0.1315
Arm speed	0.7853	0.5574
Arm speed	0.7173	0.5728
Stress	0.4518	0.7799
Stress	0.4109	0.7863