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

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Background. Improvements in data processing, increased understanding of the biomechanical background behind kinetics and kinematics, and 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 to the pitching arms 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 MotusBASEBALL device will hold a statistically significant level of reliability and accuracy, 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 wore retroreflective markers and the MotusBASEBALL sensor simultaneously.

Results. It was found that the Arm Slot (R = 0.975, P < 0.001), Shoulder Rotation (R = 0.749, P < 0.001), and Stress (R = 0.667, P = 0.001 when compared to elbow torque; R = 0.653, 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 (R = 0.668, P = 0.001) and shoulder velocity magnitude (R = 0.659, P = 0.002). For the entire sample, Arm Slot and Shoulder Rotation measurements were on a similar scale, or within 5-15% in absolute value, of magnitude to measurements from the motion capture test, averaging 8 degrees less (12.9% relative differences) and 9 degrees (5.4%) less respectively. Arm Speed had a much larger difference, averaging 3745 deg/s (80.2%) lower than shoulder internal rotation velocity, and 3891 deg/s (80.8%) less than the shoulder velocity magnitude. The Stress metric was found to be 41 Nm (38.7%) less when compared to elbow torque, and 42 Nm (39.3%) less when compared to shoulder torque. Despite the differences in magnitude, the correlations were extremely strong, indicating that the MotusBASEBALL sensor had high reliability for casual use.

Conclusion. This study attempts to validate 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 and while some magnitudes differ substantially and therefore fall short in validity, the link between the metrics is strong enough to indicate reliable casual use. Further research should be done to further investigate the validity and reliability of the Arm Speed metric.

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31   **Abstract**

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35   angles and acceleration on human subjects. This has resulted in new devices that reportedly
36   measure joint angles, arm speed, and stresses to the pitching arms of baseball players. This study
37   seeks to validate one such sensor, the MotusBASEBALL unit, with a marker-based motion
38   capture laboratory.

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42   limitations in IMU technology.

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44   curveball) in the motion capture lab. Subjects wore retroreflective markers and the
45   MotusBASEBALL sensor simultaneously.

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47   < 0.001), and Stress (R = 0.667, P = 0.001 when compared to elbow torque; R = 0.653, P = 0.002
48   when compared to shoulder torque) measurements were all significantly correlated with the
49   results from the motion capture lab. Arm Speed showed significant correlations to shoulder
50   internal rotation speed (R = 0.668, P = 0.001) and shoulder velocity magnitude (R = 0.659, P =
51   0.002). For the entire sample, Arm Slot and Shoulder Rotation measurements were on a similar
52   scale, or within 5-15% in absolute value, of magnitude to measurements from the motion capture
53   test, averaging 8 degrees less (12.9% relative differences) and 9 degrees (5.4%) less respectively.
54   Arm Speed had a much larger difference, averaging 3745 deg/s (80.2%) lower than shoulder
55   internal rotation velocity, and 3891 deg/s (80.8%) less than the shoulder velocity magnitude. The
56   Stress metric was found to be 41 Nm (38.7%) less when compared to elbow torque, and 42 Nm
57   (39.3%) less when compared to shoulder torque. Despite the differences in magnitude, the
58   correlations were extremely strong, indicating that the MotusBASEBALL sensor had high
59   reliability for casual use.

60   **Conclusion.** This study attempts to validate the use of the MotusBASEBALL for future studies
61   that look at the Arm Slot, Shoulder Rotation, Arm Speed, and Stress measurements from the
62   MotusBASEBALL sensor. Excepting elbow extension velocity, all metrics from the
63   MotusBASEBALL unit showed significant correlations to their corresponding metrics from
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65   validity, the link between the metrics is strong enough to indicate reliable casual use. Further
66   research should be done to further investigate the validity and reliability of the Arm Speed
67   metric.

68

69 **Introduction**

70 Technological advancements in the motion capture field have enabled coaches and athletes to
71 better quantify the locomotor demands of their sport. Marker-based motion capture has been
72 shown in research to be capable of measuring the kinematics and kinetics of a baseball pitch
73 (Richards, 1999). The OptiTrack camera system (Natural Motion / OptiTrack; Corvallis, Oregon)
74 used in this study has also been shown in research to be comparable to other high-end motion
75 capture systems (Thewlis et al., 2013).

76 Marker-based motion capture, however, requires technical expertise and labor, and can be
77 prohibitively expensive to many coaches and athletes. Inertial Measurement Unit (IMU) based
78 sensors have been used to quantify human movement and have undergone a lot of technological
79 improvements to become increasingly more accurate.

80 IMU sensors have been validated in research for joint angle measurements in the lower body
81 (Leardini et al., 2014), as well as in the upper body (Morrow et al., 2017). IMU sensors have
82 been validated for biomechanical analysis in movement-based areas like gait analysis (Kavanagh
83 and Menz, 2008), running kinematics (Provot et al., 2017), and swimming biomechanics (de
84 Magalhaes et al., 2014). IMU sensors have started to gain popularity in measuring the kinematics
85 of throwers, but validation of such sensors has been limited. Specifically for throwing-based
86 movements, one study placed wearable IMU sensors on the arms and measured kinematic
87 positions to determine whether a cricket bowl qualified as legal or not (Wixted et al. 2012).
88 Another study used inertial sensors to determine the peak outward acceleration of several cricket
89 bowlers (Spratford et al., 2014).

90 In baseball, one study used IMU sensors to measure kinematics of youth pitchers, but the study
91 focused primarily on pelvis and torso rotation; the sensor attached to the wrist was only used to
92 identify the timing of the throwing motion's acceleration phase (Grimpampi et al., 2016).
93 Another study compared the kinematics of 4 different pitchers with a 5-node IMU setup to an
94 optical lab, but relationships were primarily established qualitatively, and only shoulder rotation
95 speed was analyzed with any statistical rigor (Lapinski, et al. 2009). Additionally, the
96 sportSemble device used in the study is not commercially available, justifying an investigation
97 into more consumer-grade IMU-based sensors.

98 The MotusBASEBALL unit (Motus; New York, NY) is a popular IMU sensor that purports to
99 measure the biomechanics of a thrower's elbow. The only existing validation of the unit comes
100 from Camp et al., (2017), which states that the MotusBASEBALL sensor was evaluated
101 simultaneously with an 8-camera motion capture system. Correlation coefficients ('r' values)
102 between measurements with the 2 systems were found to be "good to excellent" for all
103 measurements, though no supplemental data were provided. A subsequent study used the
104 MotusBASEBALL unit to look at elbow torque and other parameters in pitchers throwing
105 fastballs and off-speed pitches, but did not provide an attempt at possible validation (Makhni et
106 al., 2018).

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

109   system. The hypothesis was that the joint angle measurements of Arm Slot and Shoulder
110   Rotation would be validated as accurate and reliable, while the Arm Speed and Stress metrics
111   might not be as accurate. The hypothesis was more optimistic about the former two
112   measurements because of the past validation research done around IMU sensors in measuring
113   position or joint angles and rotation around one axis, while being more pessimistic about the
114   latter two measurements as arm movement in three separate planes is more difficult to quantify
115   and the inclusion of acceleration in calculating stress and inverse dynamics could likely lead to a
116   propagation of errors through the multiple derivations of the position.

117   **Methods**
118   Ten healthy pitchers, all of collegiate or pro-level experience, volunteered to participate in the
119   study: nine threw overhead, one threw sidearm and all were right-handed. Participants were
120   provided a verbal explanation of the study and its risks and were asked to read and sign an
121   Informed Consent document before testing. The Informed Consent documents were generated
122   once Hummingbird IRB approved the study and granted ethical approval to carry out the data
123   collection at the author's facilities (Hummingbird IRB #: **2018-10**). Testing proceeded once
124   investigators received verbal confirmation and obtained a witnessed legal signature from the
125   athlete. Heights, weights, and ages of the participants were recorded before the beginning of
126   testing. (Table 1)

127

128   [Table 1]

129

130   *Testing Procedure*

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

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

142   The pitchers simultaneously were outfitted with the MotusBASEBALL sensor. The
143   MotusBASEBALL sensor is 38 mm in length, 25 mm in width, 10 mm in height, 6.9 grams in
144   weight, and samples at a 1000 Hz with a 3-axis accelerometer (+/- 24 G-sensitivity) and 3 axis
145   gyroscope (+/- 4000 DPS-sensitivity). Further details can be located on Motus Global's Product
146   Specs web page.

147   Said sensor is typically inserted into a sleeve that the athlete wears, so that the small arrow on the
148   sensor points towards the distal end of the athlete's throwing arm. The sleeve is then worn and
149   adjusted such that the sensor is placed over the flexor bundle of the athlete. The sleeve was not
150   used in this study because of its inability to allow for simultaneous motion capture takes. Instead,
151   the Motus sensor was fixed to the athlete in accordance with the directions on the Motus app,
152   with the designated placer strapping it two finger widths below the medial epicondyle of the
153   inside edge of the athletes throwing forearm using double sided skin-tape to avoid the sleeve
154   causing interference with any of the markers. (Figure 1)

155

156   [Figure 1]

157

158   Pitchers then threw 5-7 fastballs, followed by 5-7 off-speed pitches (either curveballs or sliders
159   dependent on each individual's comfort levels), with approximately 30-60 seconds of rest in
160   between throws. All pitches were thrown at a medium effort level. Research has shown that off-
161   speed pitches may result in significant changes to kinetics and kinematics (Escamilla et al., 2017;
162   Fleisig et al., 2006). For this reason, athletes were asked to throw their preferred off-speed pitch.
163   Fatigue was assumed to be negligible with such a low pitch count.

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

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

176

177   [Figure 2]

178

179   Joint centers of the model were estimated based on markers placed on the joint and local
180   coordinate systems (Dillman et al., 1993). Position data were filtered using a 20 Hz fourth-order
181   Butterworth low-pass filter, after which kinematics and kinetics were calculated in Visual3D (C-
182   Motion Inc., Germantown, MD). The model was scaled for body size, and inertial properties of
183   the hand, forearm, and upper arm were based on cadaveric data (de Leva, 1996). The baseball
184   was modeled as a 0.142 kg point mass at the metacarpal marker until the ball was released, while

185   after release the mass was omitted from the model (Fleisig et al., 2005). All kinematic and
186   kinetic values were calculated using the ISB recommended model of joint coordinate systems
187   (Wu et al., 2005). In total, 10 kinematic and kinetic values (3 position, 5 velocity, and 2 kinetic)
188   were calculated and the mean values of each participant's 5 clearest throws of each pitch type
189   were used (Escamilla et al., 1998).

190   Three position values for the motion capture system were all found at ball release (BR): trunk
191   lateral tilt, shoulder abduction, and shoulder external rotation. Measurements were taken as their
192   local joint angles measured in degrees. The five velocity parameters were taken as the maximum
193   speeds of shoulder internal rotation, shoulder abduction, shoulder horizontal abduction, elbow
194   angular extension and forearm angular extension, as per the precedents set from the Fleisig
195   model. All velocities were calculated as the rate of change in the joint angle, measured in
196   degrees/second. The two kinetic values calculated were the maximum elbow varus torque and
197   shoulder internal rotation torque, which were measured in Newton meters (Nm).

198   All MotusBASEBALL data were collected with an iPhone (Apple Inc., Cupertino CA) and the
199   supplied app, "Motus Throw", which was then manually transferred into labeled spreadsheets for
200   storage and later analysis. The app generated the Arm Slot, Arm Speed, Arm Stress, and
201   Shoulder Rotation metrics. Arm Slot was reported as taken at ball release while Arm Speed was
202   taken at the peak value slightly after ball release; the Arm Stress and Shoulder Rotation measures
203   were dependent on the athlete's max external rotation.

204   *Statistical Analysis*

205   The data metrics were analyzed as both a total sample of twenty (20) pitches and two separate
206   equal-sized groups classified by the type of pitch: fastballs (10) and off-speed pitches (10). Each
207   pitch was an average of the five pitches analyzed by each of the two systems in question.
208   Anticipating a difference in the scale of the respective magnitudes for the two systems, the
209   statistical analyses centered on a correlation test based around Pearson's product moment of
210   correlation coefficient and an n-2 number of degrees of freedom. The correlation test was used to
211   test the hypothesis of a linear relationship between the set of metrics obtained for each of the two
212   systems. Statistical significance was based on a default alpha value of 0.05.

213   In order to create measurement analogues between the motion capture trial and the
214   MotusBASEBALL metrics, additional calculations were done. Corrections to the metrics were
215   done following Motus's guidelines which were communicated via email by representatives from
216   Motus; those corrections follow below.

217   Arm Slot (Motion Capture system) was taken as the sum of the lateral trunk tilt and shoulder
218   abduction at BR. Shoulder Rotation was measured as the maximum amount of shoulder external
219   rotation measured in the global coordinate system. MotusBASEBALL's Arm Speed metric,
220   which was taken from the MotusTHROW app, was compared to elbow extension velocity and
221   shoulder internal rotation velocity, which are the most common standards for measuring arm
222   speed. Per Motus's recommendation, Arm Speed was also compared to the magnitude of the
223   resultant angular velocity of the shoulder, which is compromised of the following components:

224   the square root of the sum of the squares of shoulder abduction velocity, ω_{Sa}, shoulder horizontal
225   abduction velocity, ω_{Sha}, and shoulder internal rotation velocity, ω_{Sir}. $\sqrt{\omega_{Sa} + \omega_{Sha} + \omega_{Sir}}$.

226   In addition, the angular velocity of the forearm extension as taken on the motion capture system
227   as another Arm Speed metric to use based on Motus defining their arm speed metric as the
228   "resultant angular velocity of the forearm segment." MotusBASEBALL stress was compared to
229   elbow varus torque and shoulder internal rotation torque, which are the two most commonly
230   addressed kinetic markers in pitching research. All torque metrics were in Nm.

231   First, the descriptive metrics (means and standard errors of means) for the whole group and
232   subgroups for all the marker-based biomechanics measurements and MotusBASEBALL
233   measurements were outlined and recorded. Differences in magnitudes across the two systems
234   were rendered as both absolute and relative errors, where the relative error was measured as the
235   absolute error divided by the total value of the motion capture criterion system. Then these
236   metrics were matched together across paired results (each subject having been recorded on the
237   two separate systems), and had both their Pearson correlation coefficient ρ calculated along with
238   its 95% confidence interval and its associated p-value, following a Student's T test distribution.
239   The correlation test posits the hypothesis of there being a significant linear association versus the
240   null hypothesis of there being no correlation, or $\rho = 0$. Differences in magnitudes between the
241   systems are noted in the text as both absolute differences and relative percentage differences
242   between the two systems, divided by the motion capture criterion system. In addition, Bland
243   Altman plots were used for each fastball and off-speed metric comparison to investigate the
244   reliability of the two metrics despite their frequent differences in absolute magnitudes. All the
245   aforementioned statistical analysis was performed using the program open-source statistical
246   Program R (www.r-project.org).

247   **Results**
248   The results for the three separate groups are displayed in Tables 2 and 3:

249

250   [Table 2]

251

252   [Table 3]

253

254   As is somewhat intuitive given the nature of the more similar sub-populations, the correlation
255   coefficient is higher within said smaller groups, due to the smaller sample sizes and subsequent
256   degrees of freedom. The fastball group found significant associations between four of the metrics
257   (Arm Slot, Shoulder Rotation, and the second and third Arm Speed metrics), while the off-speed
258   group found significant associations between six metrics (Arm Slot, Shoulder Rotation, the
259   second and third Arm Speed metrics, and both Stress metrics). Confidence Intervals were
260   included to give a clearer picture of the correlation's reliability and confirm that the significant

261 correlations indicate some degree of positive linear relationship. Bland-Altman plots were
262 generated below in Figures 3 through 6 for analysis of the different measurement systems and
263 their subsequent reliability. Their reliability appears to be quite high as the individual data points
264 all fell within the confidence intervals of the differences between the systems' magnitudes for the
265 majority of the metrics, and no one metric had more than a single point outside of said
266 confidence intervals.

267

268 [Figure 3]

269

270 [Figure 4]

271

272 [Figure 5]

273

274 [Figure 6]

275

276 **Discussion**

277 Arm slot was found to be near perfectly correlated across all groups, though
278 MotusBASEBALL's arm slot was roughly 7-10 degrees lower than the results from our motion
279 capture system, with a relative error of 12.9%.

280 Shoulder rotation was also strongly correlated between the two systems. On average the shoulder
281 rotation measured by MotusBASEBALL was 9 degrees, or 5.4%, lower than what the motion
282 capture system detected for the total group.

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

288 The numerical difference between the two systems is fairly substantial. Average
289 MotusBASEBALL arm speed, which was 925 deg/s, was dramatically lower than the measured
290 shoulder internal rotation speeds and magnitude of both shoulder rotational velocities and
291 forearm velocities, which were 4670 deg/s, 4816 deg/s and 5744 deg/s respectively, to go along
292 with relative differences of 80.0%, 80.8%, and 83.9%. It is also worth noting that the arm speed
293 metric that MotusBASEBALL outputs in the app is different than the metric that is in their web-
294 based portal. Because MotusBASEBALL's arm speed metric in the app would scale linearly to
295 the metric in the portal, it follows that the comparison of motion capture arm speed metrics to the
296 arm speed in the app would still be reliable.

297   Both comparisons to MotusBASEBALL's Stress metric were significant. Both stress
298   measurements (from MotusBASEBALL and from motion capture) were shown to be consistent
299   across the holistic sample of subjects. Kinetics calculations are heavily dependent on the
300   athlete's height and weight, along with the weight of the ball (Feltner and Dapena, 1986). Motus
301   has stated that their calculation also takes these factors into consideration and are part of the
302   inputs required to use the MotusBASEBALL sensor. The fact that those inputs are considered
303   could explain part of the statistically significant correlation between the two stress metrics.
304   Conversely, while the stress correlation exists for the whole sample and the off-speed sub-
305   sample, it is not significant for the fastball sample; potential variables that could explain the
306   disparity in correlations include the differences across the systems in marker placement and
307   inertial parameters set in their respective algorithms.

308   Because the numerical outputs from the MotusBASEBALL unit are noticeably different from the
309   outputs from marker-based motion capture outputs, which is the gold standard of biomechanical
310   analysis, MotusBASEBALL's best use may be in relative comparisons of the same athlete. This
311   gap in absolute value potentially stems from the difference in measurement units the two systems
312   use; as the Bland-Altman plots above show, the majority of the data points fall within the 95%
313   confidence intervals for all eight metric comparisons in both the fastball and off-speed
314   populations: the only exceptions being a solo arm slot data point for both off-speed and fastball
315   pitches, and a solo data point for the fastball metric comparison of Motus's arm speed and
316   MoCap's shoulder internal rotation angular velocity. Nevertheless, these findings, while
317   supporting the reliability of the Motus metrics, fail to validate them as validation in research, by
318   definition, necessitates the magnitude of the scale to be confirmed as accurate.

319   These differences in magnitudes are likely in large part from the aforementioned escalating error
320   that stems from IMU sensors attempting to measure movement in three planes and correctly
321   quantify acceleration, the second derivative of position with respect to time. Nevertheless, there
322   are multiple instances of concurrent technologies having significant correlations, and by
323   extension acceptable reliability, while exhibiting numerical differences in absolute magnitude
324   that impede its validity (O'Donnell et al., 2018). In addition, there is also a specific history in the
325   world of baseball player development in using technology that may be highly reliable while
326   measuring outcomes on different scales of magnitude, like the tachistoscope test correlating with
327   a player's batting average (Reichow et a., 2011).

328   In addition, MotusBASEBALL has shown to be internally consistent when used by the same
329   athlete as evidenced by the subjects' individual coefficient of variation scores on their five
330   Motus-recorded throws, which makes it an efficient tool for noting significant changes to an
331   athlete's mechanics. (Table 4)

332

333   [Table 4]

334

335   While the MotusBASEBALL unit cannot replace the gold-standard of motion capture, it has a
336   significant advantage in that it can be used in live competition and practice situations without
337   serious preparation. The MotusBASEBALL unit is likely best applied by laypeople, coaches, and
338   those who do not have regular access to a sophisticated motion capture system, or the time to
339   implement said analysis.

340   *Limitations*

341   There are a few noteworthy limitations to this study. As mentioned previously, the more
342   commercial sleeve was not used to place the sensor. Using a sleeve would have prevented the
343   ability to take motion capture takes as the markers could not have been placed on the sleeve.
344   Therefore it is important for athletes and coaches to maintain the position of the sensor as they
345   throw to maintain accurate readings as movement of the sleeve from the intended sensor location
346   will likely change the readings. In addition, the soft tissue artifact can lead to errors in readings
347   for both the sensor and the aforementioned more popular sleeve, and previous literature has
348   indicated the necessary use of data filtering techniques like the Kalman Filter to eliminate much
349   the error in readings (Lin and Kulic, 2012). It is possible that similar, more thorough filtering
350   techniques would lead to even more precise Motus readings, as it is unclear what sort of filtering
351   techniques the proprietary technology does use.

352   In addition, the smaller sample size still leaves questions as to the validity of the findings and the
353   significant correlations did not always carry over across different pitch types: for example, the
354   Stress metric was significant in the off-speed pitch sample and not in the fastball pitch sample.
355   Further research should be done with a larger sample size to both further investigate the Arm
356   Speed metric in order to find a more intuitive significant correlation to a respective motion
357   capture measurement and to further investigate the large numerical differences in the angular
358   velocities of the two systems.

359   **Conclusion**
360   This results from this study show that MotusBASEBALL could be a suitable low-cost and partial
361   alternative to performing a full biomechanics capture, particularly for the arm slot, shoulder
362   rotation, and stress metrics. Arm speed was shown to have a weaker correlation to the results that
363   were found in the motion capture test. It should be noted that while all metrics from
364   MotusBASEBALL had significant variance in values when compared to the motion capture
365   metrics, the numbers were consistent for each subject and across all groups; Arm Slot averaged 8
366   degrees (12.9%) less than motion capture, Shoulder Rotation averaged 9 degrees (5.4%) less than
367   motion capture, and Stress averaged 41 (38.7%) and 42 Nm (39.3%) less than motion capture for
368   elbow torque and shoulder torque respectively. While differences in magnitudes prevented
369   validation of the Motus scores, the high reliability of these three metrics in particular could
370   reasonably be used in future studies and for use in monitoring an individual athlete's mechanics
371   from session to session.

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Participants' descriptive and performance characteristics

Biological and performance data on the subjects in the study.

1   TABLE 1: Participants' Descriptive and Performance Characteristics

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

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.

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

P-values and correlations with confidence intervals for metric comparisons

Statistical analysis of the comparisons between the Motion Capture System and the motusBASEBALL unit.

1   TABLE 3: P-Values and Correlations with Confidence Intervals for Metric Comparisons

Group	All			Fastball			Off-Speed		
Sample Size	20			10			10		
Metric	P-Value	R	R: C.I.	P-Value	R	R: C.I.	P-Value	R	R: C.I.
Arm Slot	<0.001*	0.975	[0.94,0.99]	<0.001*	0.978	[0.91,0.99]	<0.001*	0.974	[0.89,0.99]
Shoulder Rotation	<0.001*	0.749	[0.46,0.89]	0.022*	0.71	[0.15,0.93]	0.007*	0.784	[0.30,0.95]
Arm speed - Elbow Extension Speed	0.207	0.295	[-0.17,0.65]	0.341	0.337	[-0.37,0.80]	0.413	0.292	[-0.41,0.78]
Arm Speed - Shoulder Int Rot Speed	0.001*	0.668	[0.32,0.86]	0.010*	0.762	[0.25,0.94]	0.045*	0.643	[0.02,0.91]
Arm Speed - Shoulder Velocity Magnitude	0.002*	0.659	[0.31,0.85]	0.017*	0.727	[0.18,0.93]	0.041*	0.651	[0.04,0.91]
Arm Speed - Forearm Velocity Magnitude	0.309	0.239	[-0.15,0.66]	0.446	0.322	[-0.43,0.77]	0.273	0.365	[-0.39,0.79]
Stress - Varus Torque	0.001*	0.667	[0.32,0.86]	0.077	0.583	[-0.07,0.89]	0.011*	0.759	[0.66,0.83]
Stress - Shoulder IR Torque	0.002*	0.653	[0.30,0.85]	0.094	0.557	[-0.11,0.88]	0.010*	0.763	[0.26,0.94]

3   * indicates that the metric was found to be statistically significant at a P < 0.05 value

Coefficient of variation for MotusBASEBALL metrics by individual athletes

An athlete-by-athlete analysis of the coefficient of variation scores for all 5 throws across all Motus-generated metrics.

1   TABLE 4: Coefficient of Variation for MotusBASEBALL Metrics by Individual Athletes

	Fastball Pitches				Off-Speed Pitches			
Athlete	Arm Slot	Shoulder Rot	Arm Speed	Stress	Arm Slot	Shoulder Rot	Arm Speed	Stress
1	4.28%	1.22%	5.77%	2.18%	2.99%	1.36%	1.87%	1.53%
2	4.89%	1.61%	10.96%	5.10%	3.90%	1.68%	10.40%	3.37%
3	8.44%	2.62%	8.52%	3.86%	5.99%	1.62%	16.44%	10.37%
4	6.35%	2.47%	10.19%	6.58%	5.50%	0.95%	4.24%	10.57%
5	-9.32%	0.84%	5.19%	10.16%	-16.67%	0.82%	3.00%	10.68%
6	5.68%	1.39%	9.90%	10.01%	17.89%	2.11%	8.74%	5.83%
7	3.33%	1.82%	4.84%	12.00%	4.08%	1.39%	2.32%	3.93%
8	7.84%	1.03%	10.12%	2.37%	9.04%	1.59%	10.72%	13.93%
9	3.31%	1.68%	6.13%	6.25%	2.52%	0.97%	8.31%	6.75%
10	3.33%	1.79%	9.04%	7.38%	2.88%	1.69%	2.77%	2.01%

Figure 1

Placement of the motusBASEBALL sensor on the elbow

How the motusBASEBALL sensor was affixed to the arm using adhesive instead of the provided sleeve. Photo by Marques Gagner.

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. Each of the 15 individual cameras identified by squares for clearer black-and-white rendering of the image. Photo by Marques Gagner.

Figure 3

Bland-Altman plots for fastball arm speed comparisons

Bland-Altman Plots among the fastball pitches for all four motion capture measurements compared to the Motus Arm Speed Metric: Elbow Angular Velocity, Shoulder Internal Rotational Velocity, Shoulder Angular Velocity, and Forearm Extension Velocity.
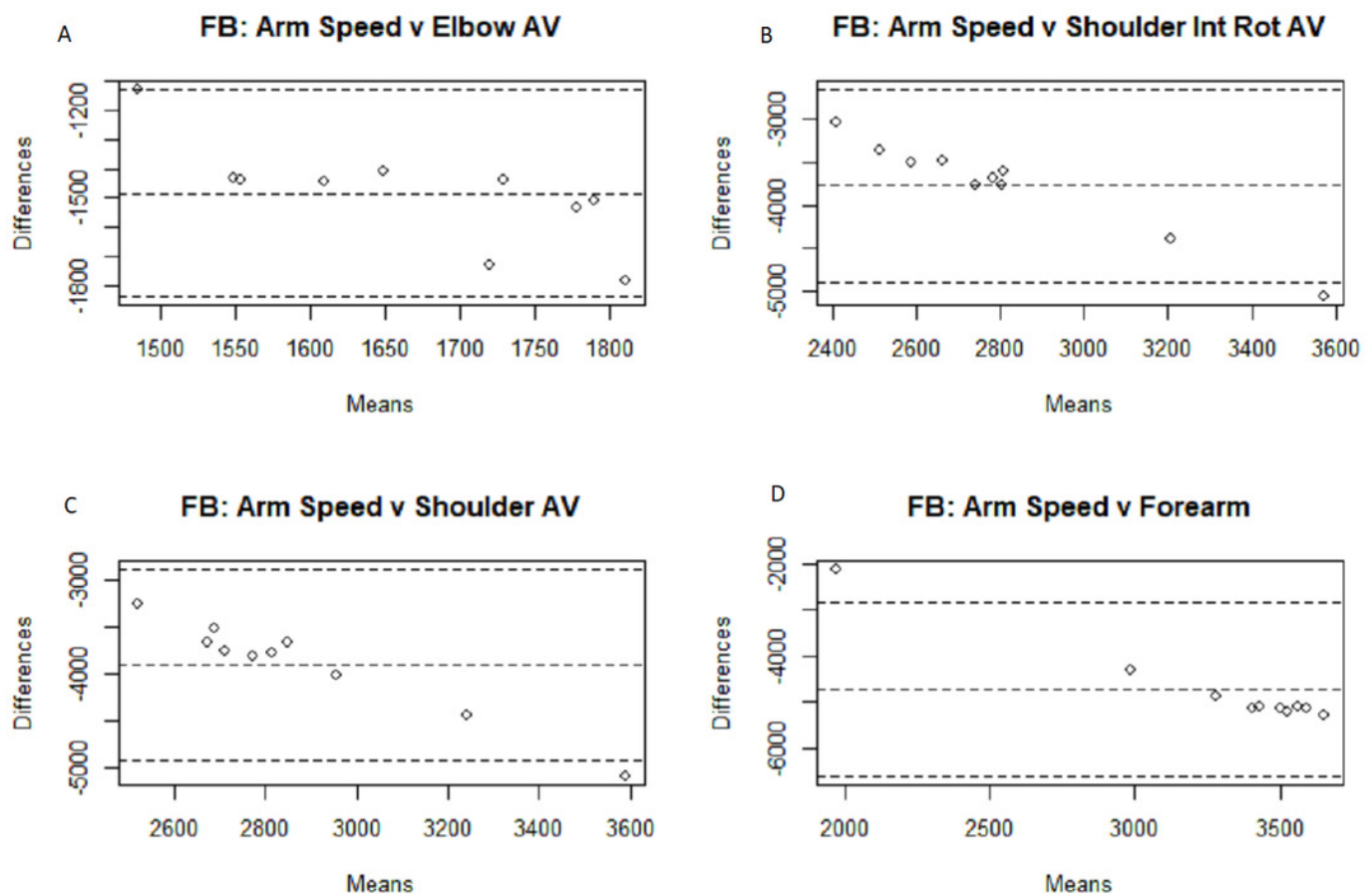
Figure 4

Bland-Altman fastball arm slot, shoulder rotation, and arm stress comparisons

Bland-Altman Plots among the fastball pitches for the Arm Slot, Shoulder Rotation, and Arm Stress (against Elbow Varus Torque and Shoulder Internal Rotation Torque) Motus comparisons
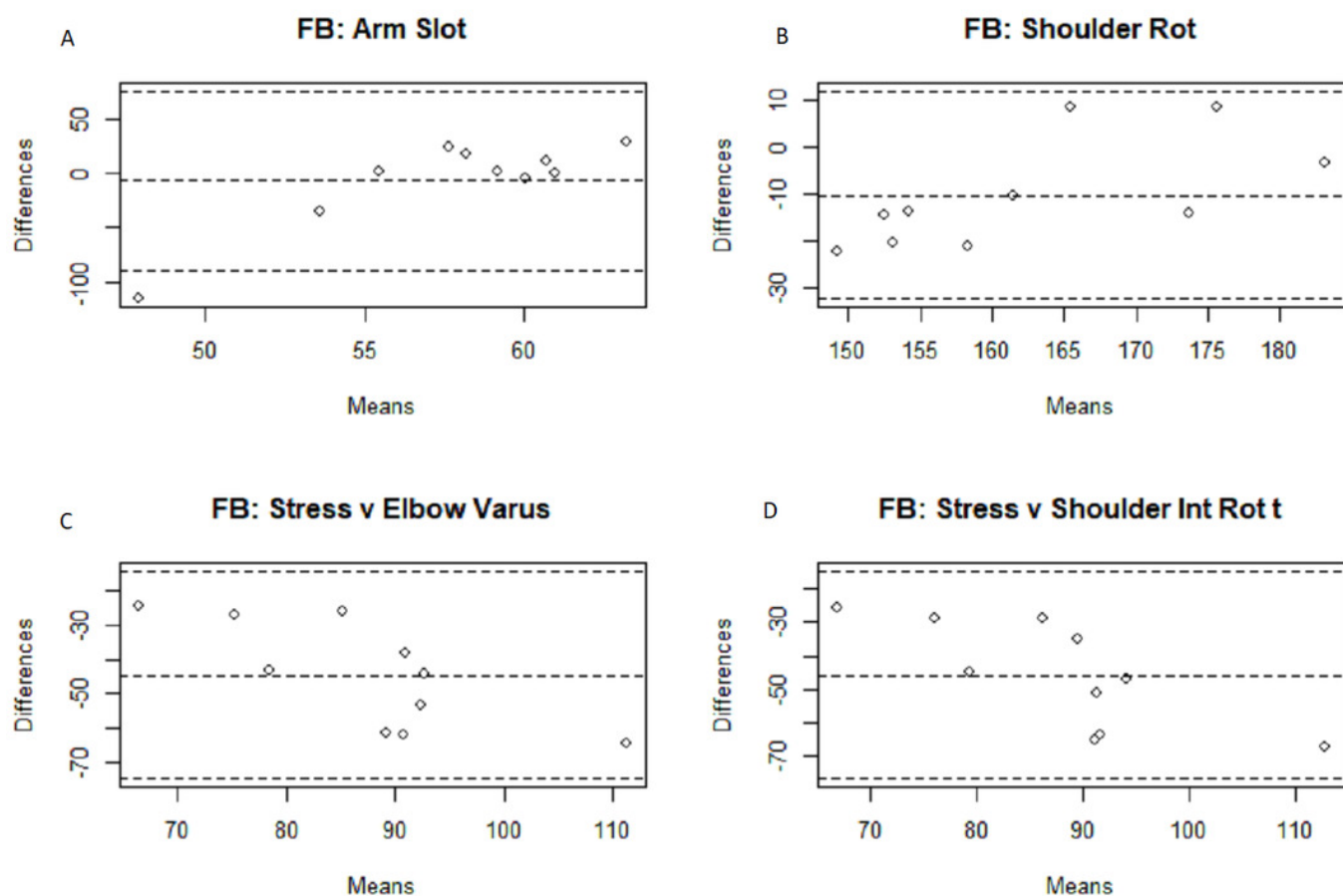
Figure 5

Bland-Altman plots for off-speed arm speed comparisons

Bland-Altman Plots among the off-speed pitches for all four motion capture measurements compared to the Motus Arm Speed Metric: Elbow Angular Velocity, Shoulder Internal Rotational Velocity, Shoulder Angular Velocity, and Forearm Extension Velocity.
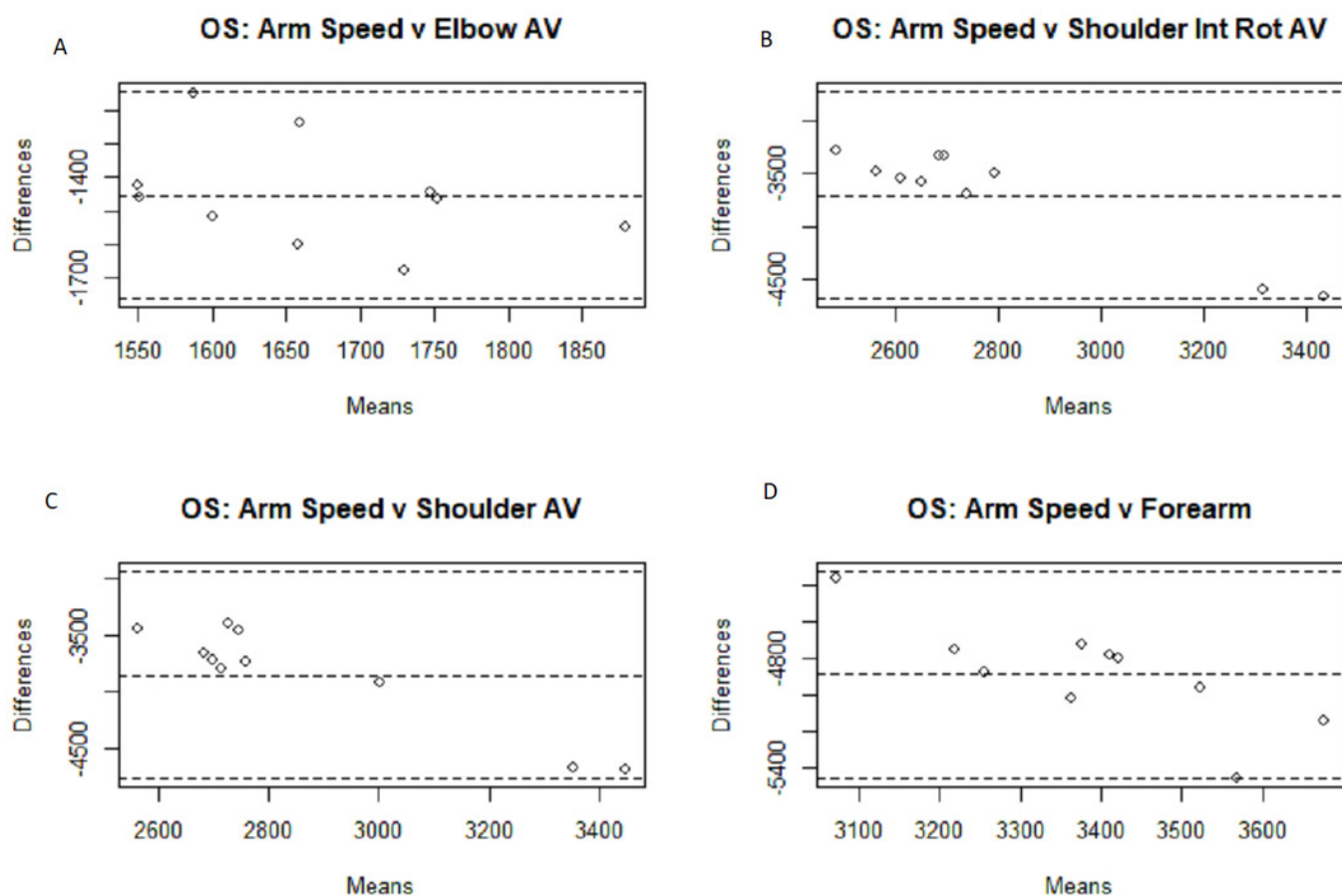
Figure 6

Bland-Altman off-speed arm slot, shoulder rotation, and arm stress comparisons

Bland-Altman Plots among the off-speed pitches for the Arm Slot, Shoulder Rotation, and Arm Stress (against Elbow Varus Torque and Shoulder Internal Rotation Torque) Motus comparisons