The Validity of Instrumented Medicine Ball Measurements

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Introduction

Weighted exercise balls, or medicine balls, are a popular training tool for a variety of exercise and therapy applications. The use of medicine balls for performance training can be dated back thousands of years to ancient Persia, where wrestlers and gladiators would throw sand-filled bladders to demonstrate physical prowess. While the composition of the ball may have changed over the previous centuries, the concept of throwing a weighted instrument such as a ball to examine power in open-chain exercises has remained a vital part of many strength and conditioning programs. Exercises using medicine balls usually consist of throwing the ball with maximum effort as part of a coordinated movement that is representative of an athletes' athletic requirements. Although the use of the medicine ball in training is common, the instrument's simplicity and the training setting make it challenging to quantify metrics related to sports performance, athletic development, or rehabilitation progress.

Previous research has demonstrated the importance of medicine ball throw performance in rehabilitation and measures of coordinated power. Seated medicine ball throws have been shown to be a reliable and valid measure of upper extremity power in athletes and older populations when looking at total throw distance. Overhead medicine ball throw distance has also shown strong correlations to countermovement vertical jump power in volleyball players. Distance of the throw is commonly used to assess medicine ball performance because of the ease with which it can be measured and the limited availability and portability of more complex measurement devices such as radar guns and motion capture (MoCap) systems. However, throw distance can be influenced by factors, such as release height and launch angle, making it a crude estimate of the velocity and power produced by the thrower. Being able to measure metrics in the gym or clinic setting would provide trainers and clinicians a more detailed understanding of the physical capabilities possessed by the athlete or patient.

The Ballistic Ball, an instrumented medicine ball manufactured by FIT7502, contains an inertial measurement unit (IMU) in the center of the ball (Patent: US9135347). The ball works by transmitting acceleration and gyroscope data from the IMU to a mobile application via Bluetooth where the data can be used to quantify various metrics from each throw such as power, speed, force, launch angle, and distance thrown. The user can select from multiple throw options standard in training and rehabilitation and track performance from many available metrics throughout a single workout or longitudinally. The versatility of the ball, combined with its ease of use, makes it a favorable option for trainers, clinicians, and individuals interested in measuring more than just throw distance from medicine ball exercises. Despite the potential utility of the Ballistic Ball, the various outputs from the ball's IMU and FIT7502's latest algorithm need to be validated. Therefore, the purpose of this investigation was to assess the validity of different Ballistic Ball throw metrics performed across a range of exercises and conditions.

Methods

IMU Algorithm

The algorithm was developed for use in the FIT7502 family of products and mobile applications. The objective of the algorithm is to take raw IMU data and transform it such that medicine ball throws can be interpreted in the global coordinate system for performance and rehabilitation monitoring purposes. This updated method will support existing Ballistic Ball products as well as the next generation of hardware from FIT7502 estimated to launch in the middle of 2021.

Participants

Data was collected primarily from one healthy participant familiar with medicine ball-related training and exercises (sex: male, age: 26 years, weight: 175 lbs, height: 69.5 inches). The participant had been familiarized with all movements before the time of data collection.

Equipment

Data was collected in two locations: a biomechanics lab and a training facility where vertical throws could be executed with max effort. Optical motion capture (MoCap) was used simultaneously to collect 3D positional data of the medicine ball with eight motion capture cameras (Oqus 7+, Qualisys AB, Sweden) operating at a frequency of 300 Hz. The capture volume was calibrated before all data collection sessions with a measurement error of <1.0mm accepted. Two medicine balls were used for data collection: one weighed 10 pounds (4.54 kg) with an approximate circumference of 39.5 inches, and one weighed approximately 6.61 pounds (3 kg) with a circumference of 28.5 inches. A set of 13 retroreflective markers were placed on each medicine ball, including a cluster of four tracking markers, two separate clusters of three tracking markers, and three markers along the radius of the ball to define the spherical shape.

Data Collection

All vertical throws were collected on a single day in the training facility, while all other throws were collected in a biomechanics lab approximately one week later. Before data collection, static trials for each ball were recorded. Three different types of throws were collected, including vertical, rotational, and chest pass. For each type of throw, a concentric-only (static) and an eccentric-concentric (dynamic) condition was recorded. The subject performed two sets of six repetitions for each throw type and condition, at both maximal and submaximal intensities. This protocol was completed with both medicine balls. For the rotational throw static condition, one additional set of six reps with each ball was performed at maximal effort to mimic a "shot-put" type throw for a total of 156 recorded medicine ball throws (Table 1).

Table 1. Testing matrix for data collection.

Movement	Vertical	Rotational	Chest Pass
Ball Sizes	2	2	2
Conditions	2	2	2
Intensities	2	2	2
Total Reps (n)	48	60	48

Data Processing

Motion capture data was processed for the duration of each repetition for all movements. The markers' raw position data was exported from the motion capture software to Visual 3D (C-Motion, Germantown, MD) for analysis. Three-dimensional models were created for each ball using the static trials and marker positions to allow for the center of mass (COM) of the ball to be used for data calculation. The position data for all motion trials was then filtered with a fourth-order lowpass Butterworth filter, corresponding to the filter applied to the IMU data by the algorithm to remove noise. Position data from the COM of the ball was then derived to obtain velocity and acceleration data for all trials collected.

All variables reported in the FIT7502 application were calculated in Visual 3D. Peak speed was calculated as the maximum value of the magnitude of the velocity vector between start and release for each throw. POP-100™, a proprietary variable of FIT7502, was calculated as the instantaneous speed of the ball at the 100 millisecond time point of the concentric phase of the throw. Launch angle was determined using the horizontal and vertical velocities at the instant of ball release using standard kinematic equations. Additionally, power, force, and work were calculated using the ball's acceleration vector and known mass. A total of 21 variables were calculated in Visual 3D; however, only peak speed, POP-100™, and launch angle were used for analysis in the current investigation. The same variables output from the company's smartphone application were exported and used for analysis.

Statistical Analyses

All statistical analyses were performed in Matlab 2020a (Mathworks, Natick, MD). Descriptive statistics (mean and standard deviation) were calculated for all variables from each system (motion capture vs. IMU) at each intensity for each exercise and condition. Data was assessed in groups based on exercise, condition, intensity, ball size, and as a whole. A series of analysis of variance (ANOVA) tests were used to determine differences between devices and the effect of the device, exercise performed, condition of the exercise (static or dynamic), intensity, ball size, and potential interaction effects. ANOVA tests were performed for each variable. A combination of Pearson's correlation, linear regression, and Bland-Altman analyses was applied to each of the variables in each respective group to assess the between device agreement. Pearson's r values were calculated and interpreted with thresholds as follows: 0-0.1, 0.1-0.3, 0.3-0.5, 0.5-0.7, 0.7-0.9, and 0.9-1.0 corresponding to no, small, moderate, large, very large, and nearly perfect agreement. The alpha level was set *a priori* as $p<0.05$.

Results

Descriptive statistics for each movement, condition, intensity, and for each variable between systems are provided in Table 2. The series of ANOVA tests revealed no significant differences between devices for peak speed with no significant interaction of devices for exercises, conditions, intensities, and ball sizes. POP-100^{TM} was significantly affected by the interaction of the device ($F = 47.57$, $p < 0.01$), condition, and ball size, as well as by the interaction of the device, movement, and ball size ($F = 10.81$, $p < 0.01$); Bonferroni *post hoc* analysis revealed significant differences between devices, $p<0.01$. Simple main effects revealed a significant difference for

POP-100^{TM} between devices for the chest pass exercise in the static condition at maximal intensity with the smaller ball ($p < 0.05$, Table 2). Launch angle was significantly affected by the interaction of the device, movement, and condition ($F = 8.61$, $p < 0.01$); Bonferroni *post hoc* analysis revealed significant differences between devices, $p=0.049$. Simple main effects revealed a significant difference for launch angle between devices for the chest pass exercise in the dynamic condition at submaximal effort with the larger ball size ($p < 0.05$, Table 2). Linear regression, Bland-Altman, and Pearson statistics for each movement and each variable and for all movements all intensities and all variables can be found in the Appendix.

When considering all intensities and all movements, a near-perfect relationship existed between devices for peak speed and launch angle, $r=0.98$, and $r=0.99$, respectively. A very large agreement existed between devices across all trials for POP-100^{TM} ($r = 0.88$). Bland-Altman analysis across all intensities for all movements indicated significant bias for all three metrics. The IMU under-reported peak speed by 0.04 m/s and POP-100^{TM} by 0.11 m/s compared to the motion capture system on average ($p < 0.05$ and $p < 0.01$, respectively). The IMU over-reported launch angle by 1.3 degrees compared to the motion capture system on average across all throws ($p = 0.01$).

For all throws in the dynamic condition, a near-perfect relationship existed between devices for peak speed, POP-100^{TM}, and launch angle across all intensities, $r=0.98$, $r=0.98$, and $r=0.99$, respectively. Bland-Altman analysis revealed no significant bias between devices for peak speed, POP-100^{TM}, and launch angle variables measured in the dynamic condition across all exercise types and intensities.

For all throws in the static condition, a near-perfect relationship existed between devices for peak speed and launch angle across all intensities, $r=0.99$ and $r=0.99$, respectively. No relationship was present for the case of POP-100™ across all intensities, r=0.07. Bland-Altman analysis revealed significant bias between devices for all three variables measured in the static condition across all exercise types and intensities. On average, the IMU under-reported peak speed and POP-100™ by 0.07 and 0.42 m/s, respectively, compared to the motion capture system ($p < 0.01$). The IMU over-estimated launch angle by an average of 2.3 degrees on average compared to the motion capture system ($p < 0.01$).

When considering all throws at maximal intensities, a near-perfect relationship existed between devices for peak speed and launch angle across all exercises and conditions, r=0.98 and r=0.99, respectively. A very large agreement was present between devices at maximal intensity for POP-100™, r=0.86. Bland-Altman analysis revealed no significant bias between devices for peak speed for all throws at maximal intensity. Significant bias was found between devices for the POP-100™ and launch angle variables with the IMU under-reporting POP-100™ by 0.11 m/s on average and over-reporting launch angle by an average of 1.5 degrees when compared to the motion capture system ($p < 0.01$).

For all throws performed at submaximal intensity, a near-perfect relationship existed between devices for peak speed, POP-100™, and launch angle, r=0.97, r=0.90, and r=0.99, respectively. Bland-Altman analysis revealed no presence of bias between devices for peak speed and launch angle for submaximal intensity throws. Significant bias ($p < 0.01$) was present between devices for POP-100™ at submaximal intensity with the IMU under-reporting POP-100™ by 0.11 m/s on average compared to the motion capture system. Additional linear regression and Bland-Altman analyses for each throw type, condition, and ball size can be found in the Appendix.

Table 2. Mean ± standard deviations (SD) for the metrics captured at each intensity and exercise for both devices.

Exercise	Condition	Ball Size	Intensity	Device	Peak Speed (m/s)	POP-100™ (m/s)	Launch Angle (degs)
Vertical	Static	3 kg	Submax	IMU	7.51 ± 0.19	0.21 ± 0.13	81.94 ± 2.83
				MoCap	7.76 ± 0.17	1.03 ± 0.44	86.69 ± 1.61
			Max	IMU	8.64 ± 0.59	0.56 ± 0.27	79.82 ± 4.07
				MoCap	8.79 ± 0.65	1.21 ± 0.45	81.99 ± 2.36
		10 lb	Submax	IMU	6.38 ± 0.17	0.18 ± 0.13	81.54 ± 2.82
				MoCap	6.47 ± 0.15	0.60 ± 0.07	88.01 ± 1.23
			Max	IMU	7.63 ± 0.12	0.20 ± 0.10	78.73 ± 5.61
				MoCap	7.82 ± 0.58	0.62 ± 0.24	79.74 ± 4.20
	Dynamic	3 kg	Submax	IMU	7.65 ± 0.34	0.57 ± 0.16	85.94 ± 1.73
				MoCap	7.66 ± 0.36	0.50 ± 0.08	85.43 ± 2.50
			Max	IMU	9.41 ± 0.42	0.91 ± 0.09	82.40 ± 5.26
				MoCap	9.41 ± 0.45	0.94 ± 0.11	85.43 ± 3.89
		10 lb	Submax	IMU	7.14 ± 0.12	0.66 ± 0.26	85.18 ± 1.98
				MoCap	7.14 ± 0.15	0.68 ± 0.30	87.85 ± 1.64
			Max	IMU	8.40 ± 0.35	0.83 ± 0.09	79.41 ± 4.10
				MoCap	8.35 ± 0.26	0.75 ± 0.02	83.61 ± 4.51
Rotational	Static	3 kg	Submax	IMU	6.40 ± 0.55	0.12 ± 0.10	26.90 ± 7.80
				MoCap	6.72 ± 0.58	0.38 ± 0.27	24.99 ± 4.37
			Max	IMU	7.41 ± 1.04	0.51 ± 1.31	22.31 ± 4.39
				MoCap	7.56 ± 0.92	0.62 ± 0.49	18.32 ± 3.32
		10 lb	Submax	IMU	5.14 ± 0.26	0.24 ± 0.09	25.41 ± 3.35
				MoCap	5.37 ± 0.33	0.42 ± 0.27	21.75 ± 2.43
			Max	IMU	6.15 ± 0.79	0.13 ± 0.06	22.49 ± 5.30
				MoCap	6.33 ± 0.84	0.32 ± 0.32	17.81 ± 4.11
	Dynamic	3 kg	Submax	IMU	6.99 ± 0.31	1.15 ± 0.30	22.87 ± 5.74
				MoCap	7.07 ± 0.29	0.54 ± 0.33	25.06 ± 3.18
			Max	IMU	8.99 ± 0.57	1.63 ± 0.30	19.03 ± 4.03
				MoCap	8.85 ± 0.32	0.85 ± 0.17	20.21 ± 2.31
		10 lb	Submax	IMU	6.26 ± 0.33	0.62 ± 0.31	23.02 ± 5.68
				MoCap	6.22 ± 0.25	0.41 ± 0.16	24.49 ± 3.03
			Max	IMU	7.56 ± 0.14	0.72 ± 0.15	19.18 ± 3.02
				MoCap	7.71 ± 0.21	0.78 ± 0.12	19.41 ± 3.41
Chest Pass	Static	3 kg	Submax	IMU	5.20 ± 0.36	0.30 ± 0.23	21.84 ± 3.31
				MoCap	5.16 ± 0.40	0.90 ± 0.76	17.44 ± 3.78
			Max	IMU	5.96 ± 0.23	0.43 ± 0.16	17.00 ± 2.65
				MoCap	5.92 ± 0.19	1.52 ± 0.47	13.41 ± 1.14
		10 lb	Submax	IMU	4.13 ± 0.18	0.19 ± 0.13	19.92 ± 5.28
				MoCap	4.05 ± 0.15	0.48 ± 0.28	18.51 ± 4.21
			Max	IMU	5.00 ± 0.20	0.39 ± 0.19	12.87 ± 2.44
				MoCap	4.85 ± 0.12	1.26 ± 0.51	12.05 ± 2.37
	Dynamic	3 kg	Submax	IMU	5.42 ± 0.32	3.60 ± 0.38	28.41 ± 2.95
				MoCap	4.90 ± 0.15	3.70 ± 0.22	20.89 ± 3.25
			Max	IMU	6.62 ± 0.38	4.98 ± 0.28	15.89 ± 4.65
				MoCap	6.47 ± 0.19	5.08 ± 0.26	13.42 ± 3.86
		10 lb	Submax	IMU	3.99 ± 0.32	2.54 ± 0.18	24.27 ± 6.12
				MoCap	4.13 ± 0.18	2.60 ± 0.17	14.88 ± 3.49
			Max	IMU	5.88 ± 0.41	3.74 ± 0.39	17.85 ± 2.71
				MoCap	5.72 ± 0.09	3.63 ± 0.29	11.76 ± 1.67

MoCap = Qualisys Motion Capture system

Discussion

The purpose of this investigation was to explore the validity of the metrics reported from the Ballistic Ball across a variety of throws and conditions. Peak speed had near-perfect agreement between devices across all conditions tested. Launch angle demonstrated good to near-perfect agreement between devices varying with exercise type and condition. POP-100™ exhibited the greatest variability in agreement between devices with near-perfect agreement present for dynamic throws and no relationship between devices when assessing static throws only. Significant bias was identified in each metric when looking at all throws; however, relative to the magnitude of the values being evaluated, this bias was negligible for most applications. Nonetheless, users of the Ballistic Ball need to be aware of both the strengths and weaknesses of the device such that they can be confident in the outputs when implementing it as a feedback or measurement tool.

POP-100™ is the instantaneous speed of the ball at the 100 millisecond point of the concentric portion of the throw and is reported across most of FIT7502's technology and exercise options. The investigation showed that overall, POP-100™ was a valid measurement across all reps performed ($r = 0.88$). Separating throws into dynamic and static conditions demonstrates differing levels of agreement between devices, with dynamic throws being more valid than static ($r = 0.98$ vs. $r = 0.07$, respectively). POP-100™ measured in all dynamic throws presented near-perfect agreement between devices with no presence of bias while static throws exhibited almost no agreement between devices with significant bias present. These results suggest that the POP-100™ metric is a valid measurement in Ballistic Ball throws where an eccentric and concentric phase are both present, but not in throws with a concentric phase alone (static throws).

The launch angle for medicine ball throws can significantly influence throw distance and is a new metric calculated in Ballistic Ball throws. Overall, launch angle presented near-perfect agreement across all throws completed and for both static and dynamic conditions ($r = 0.99$ for all). Significant bias was present when considering all throws with the IMU under-reporting launch angle for vertical throws and over-reporting launch angle for all other throw types ($p = 0.01$). Looking only at vertical throws, significant bias was observed with the IMU under-reporting launch angle by an average of 2.6 degrees ($p < 0.01$). When considering chest pass and rotational throws, significant bias was present in each exercise ($p < 0.01$ for both), with the IMU over-reporting launch angle by 4.5 and 2.2 degrees on average, respectively. While these findings are statistically significant, it is unlikely that the bias present in the launch angle metric in these exercises is influential enough to cause an error in training or clinical judgments by an end-user. The results from this investigation suggest that the novel launch angle metric is valid for all Ballistic Ball throws, but the user should be aware of the bias present in the device for the various types of throws.

Arguably the most relevant metric reported from the Ballistic Ball data is the peak speed of the throw. Speed and velocity are used across a myriad of sport and training applications as indicators of performance. As such, quantifying speed accurately in medicine ball training may provide a robust opportunity to monitor athletic development or rehabilitation progress. Peak speed showed near-perfect agreement between devices across every exercise, condition, ball size, and effort level ($r = 0.93 - 0.99$ for all). Significant bias was present across all reps ($p = 0.04$), with the IMU under-reporting peak speed by 0.04 m/s on average. In other throws, significant bias was found, with the average difference in peak speed being between -0.21 and 0.10 m/s varying with the exercise (Appendix). The mean peak speed for all throws was 6.67 m/s indicating that the IMU was biased to under-report peak speed by an average of 0.6% (mean under-reporting value divided by mean peak speed), well within an acceptable range for training and research applications. The results from this investigation suggest that peak speed reported from the Ballistic Ball is a valid measurement across all exercises, intensities, and conditions within which the ball can be used.

This investigation is not without limitations. Specifically, not all exercises offered by the IMU's mobile application were examined. Other exercises available to users include bench throw and "wall ball" throws, which were not tested. However, since these throws happen in the same plane as others examined in this paper, similar trends would likely be present in those other exercises. Additionally, a relatively small number of repetitions were collected with only one subject across these exercises, which could potentially result in Type II error due to low statistical power. Future investigations should include hundreds or thousands of trials across multiple throw constraints (efforts, launch angles, etc.) with a larger sample of athletes to assess the device's validity with greater confidence. Only a small number of available metrics were analyzed for validity assessment of the product even though the mobile application allows a user to collect many additional metrics. However, since the chosen metrics are calculated directly from acceleration outputs from the IMU, it is plausible that other metrics mathematically related to these (such as power and force) follow similar validity trends to those assessed in the current investigation. These additional metrics were calculated, and further analyses could be performed to confirm or reject this claim.

Conclusion

The purpose of this investigation was to assess the validity of the metrics calculated from the FIT7502 Ballistic Ball using the latest algorithm for computation. Results from this investigation suggest that the algorithm-IMU product provides valid measurements of peak speed and launch angle across a range of exercises, conditions, and effort levels. Specifically, across all trials, a near-perfect agreement between the IMU and gold-standard motion capture system was observed for peak speed and launch angle, with significant but relatively small bias present. POP-100^{TM} was also found to be a valid measurement for throws containing a countermovement as part of the throw condition, with near-perfect agreement again found between devices. However, the POP-100^{TM} metric should be assessed with caution in static throwing conditions as no agreement was observed between devices. Future development is warranted to more accurately assess POP-100^{TM} for static throws using the Ballistic Ball. The remaining metrics evaluated in this paper can be used and monitored with confidence by Ballistic Ball users as demonstrated by the high correlations and comparatively low levels of bias present in the measured throws.

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Appendix

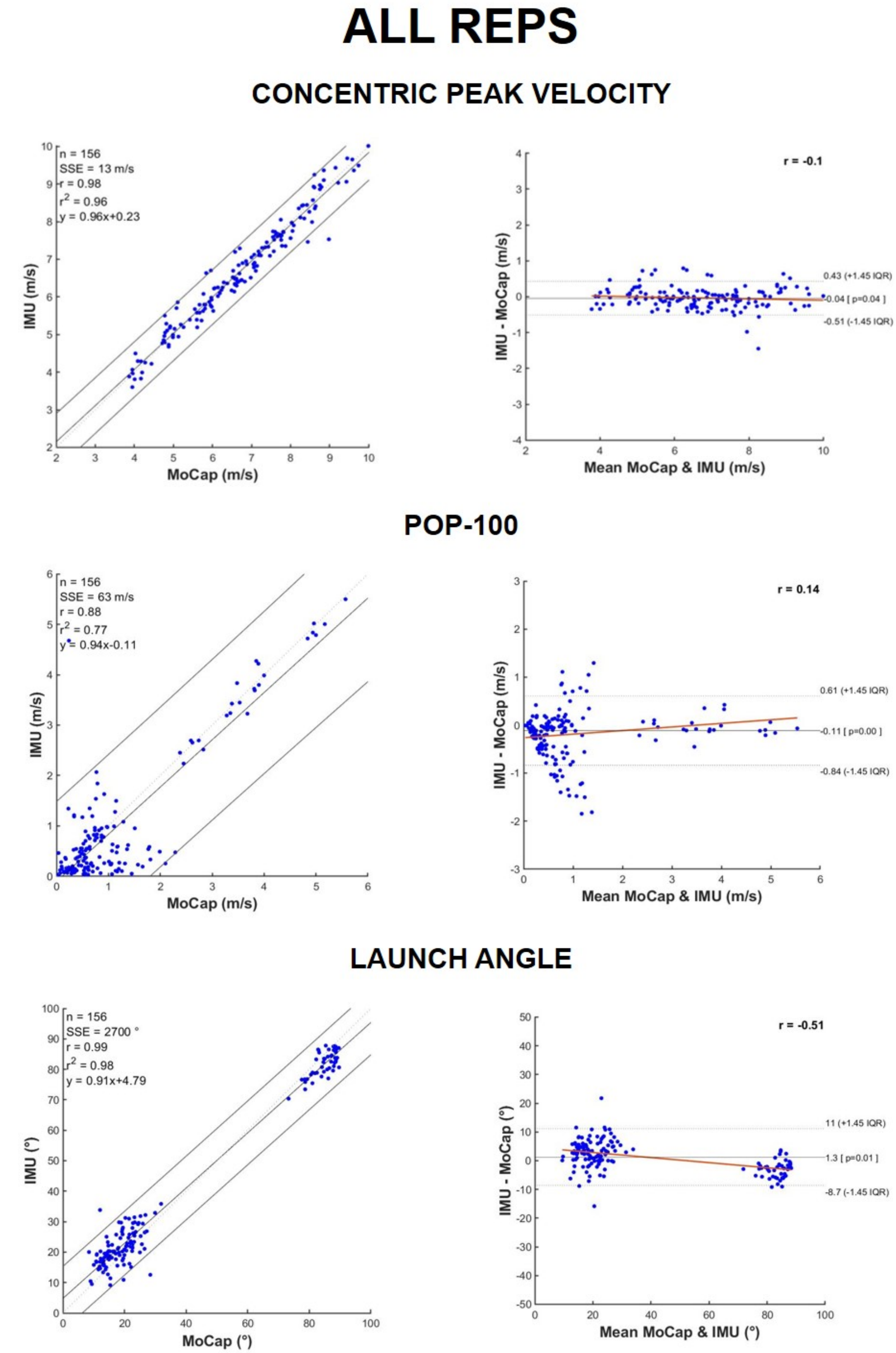

Figure 1. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all metrics recorded across all trials.

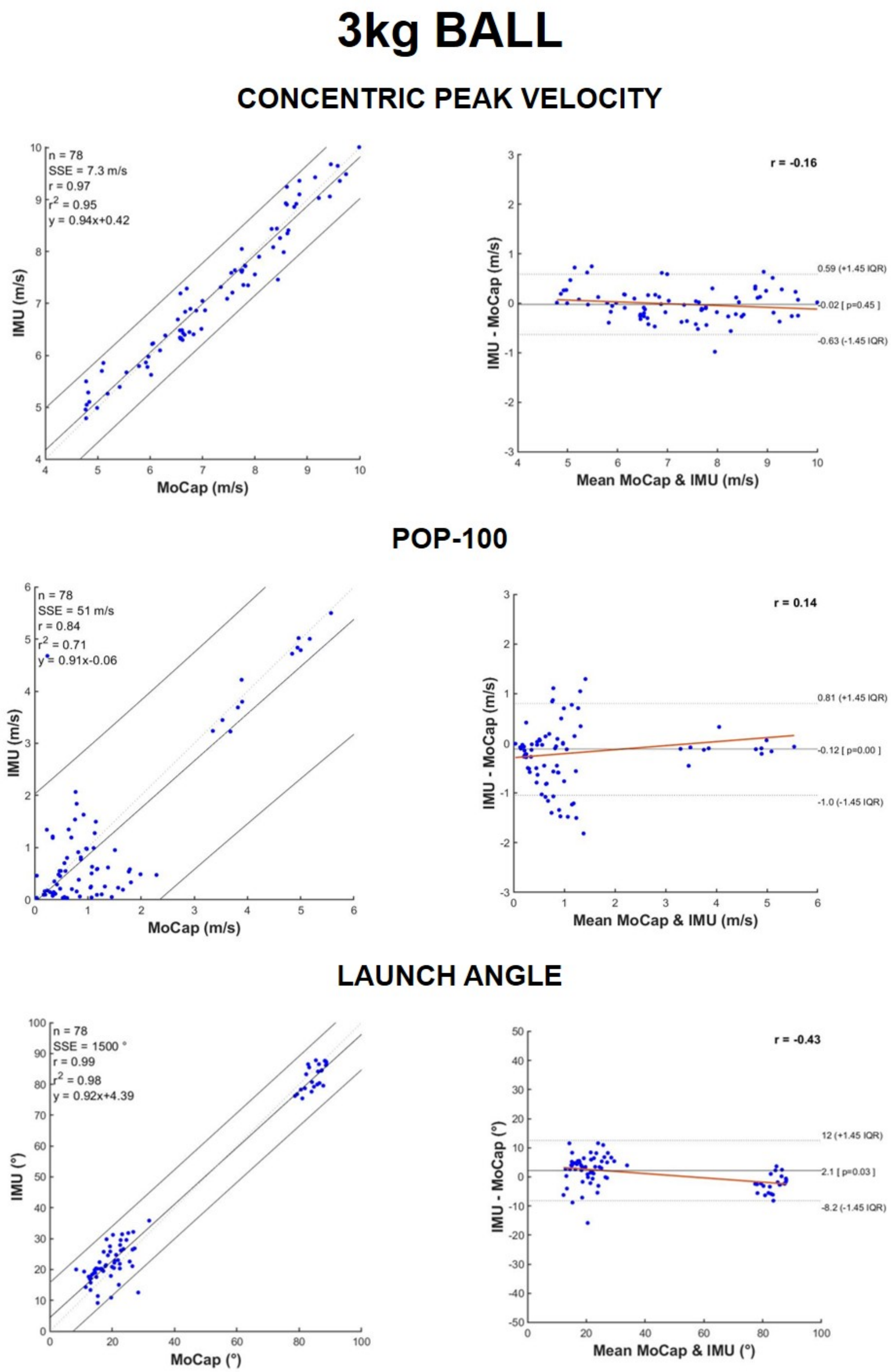

Figure 2. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all throws performed with the 3kg medicine ball.

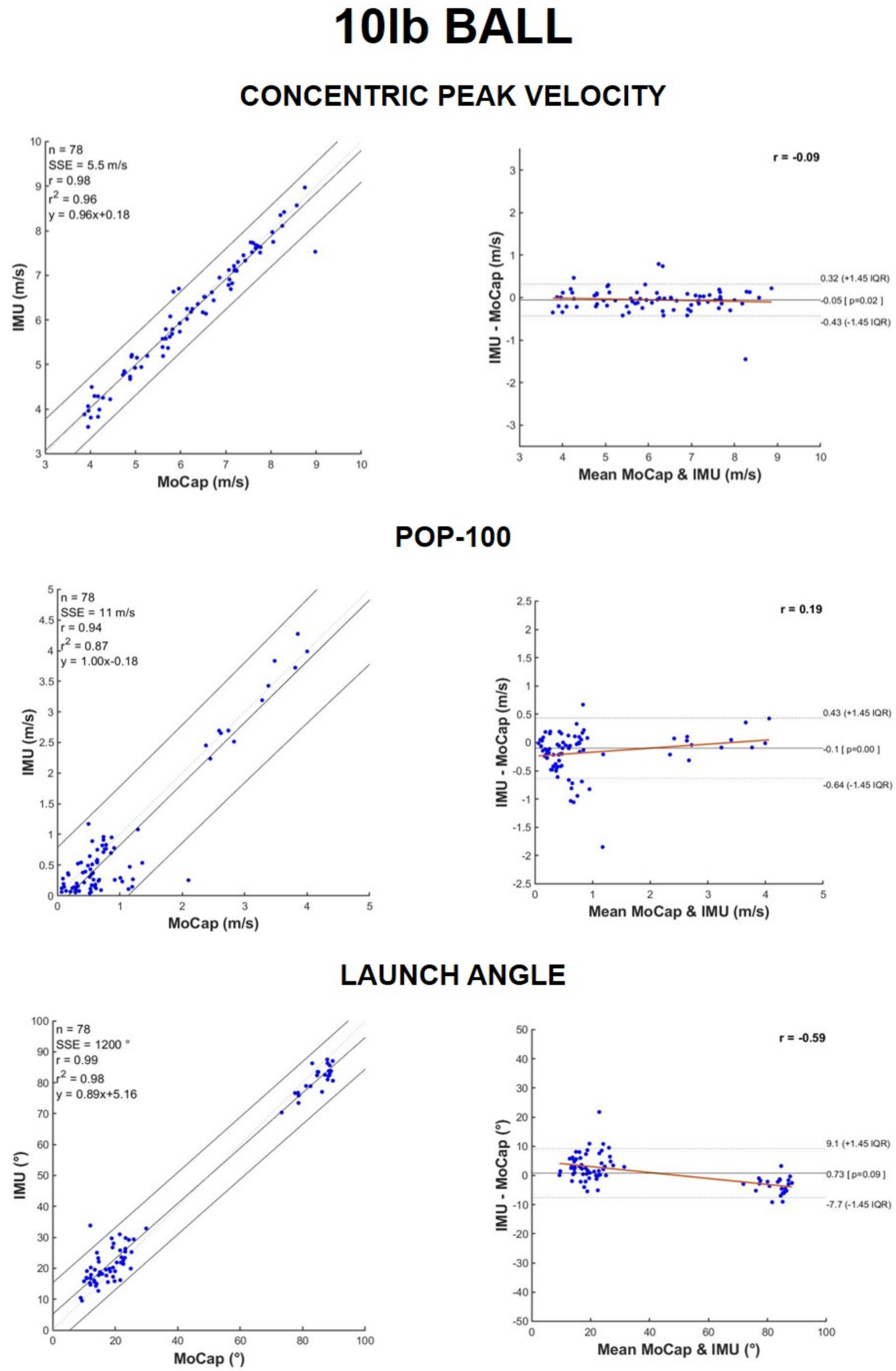

Figure 3. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all throws performed with the 10lb medicine ball.

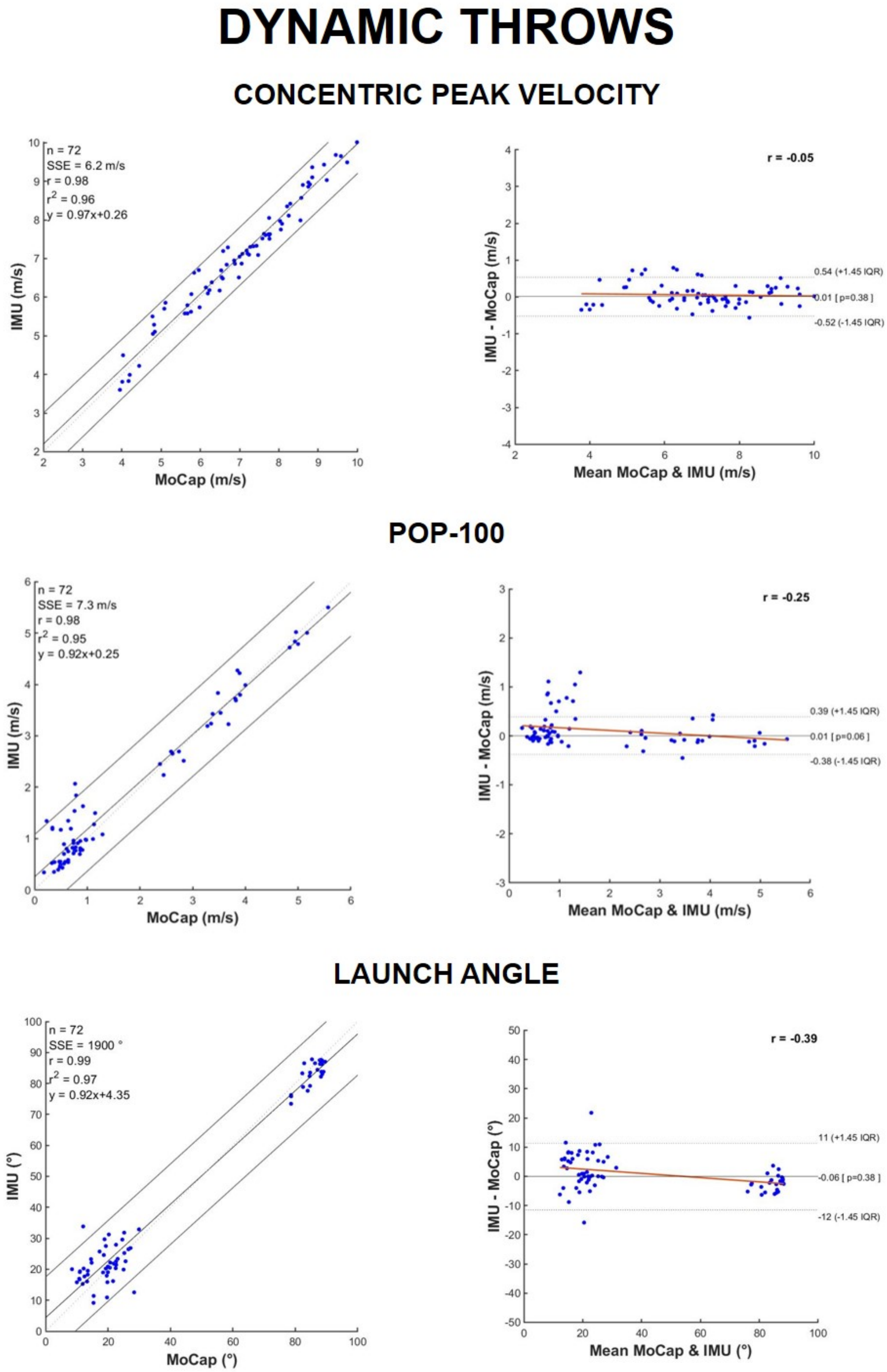

Figure 4. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for throws performed at maximal intensity.

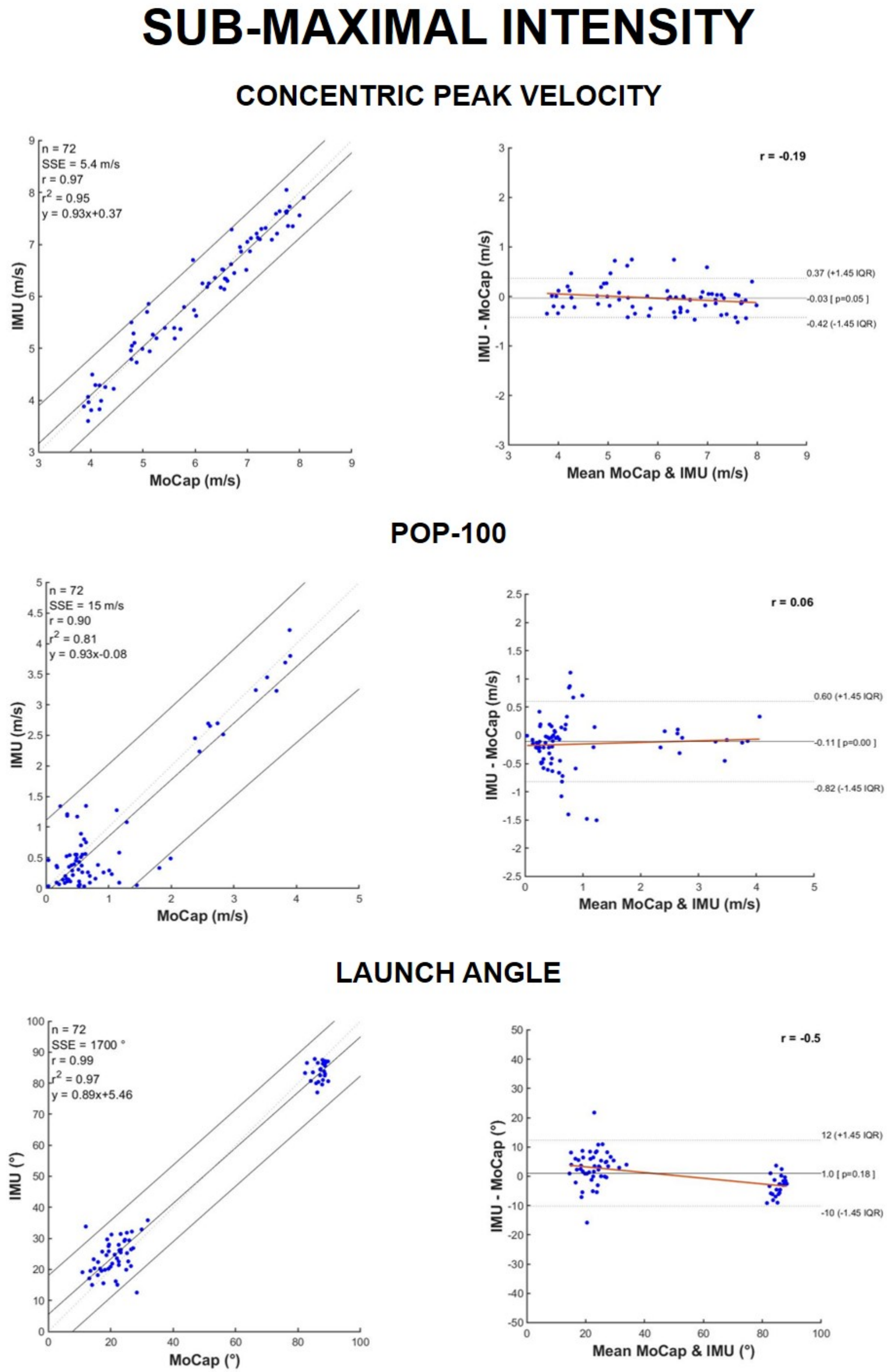

Figure 5. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all throws performed at sub-maximal intensity.

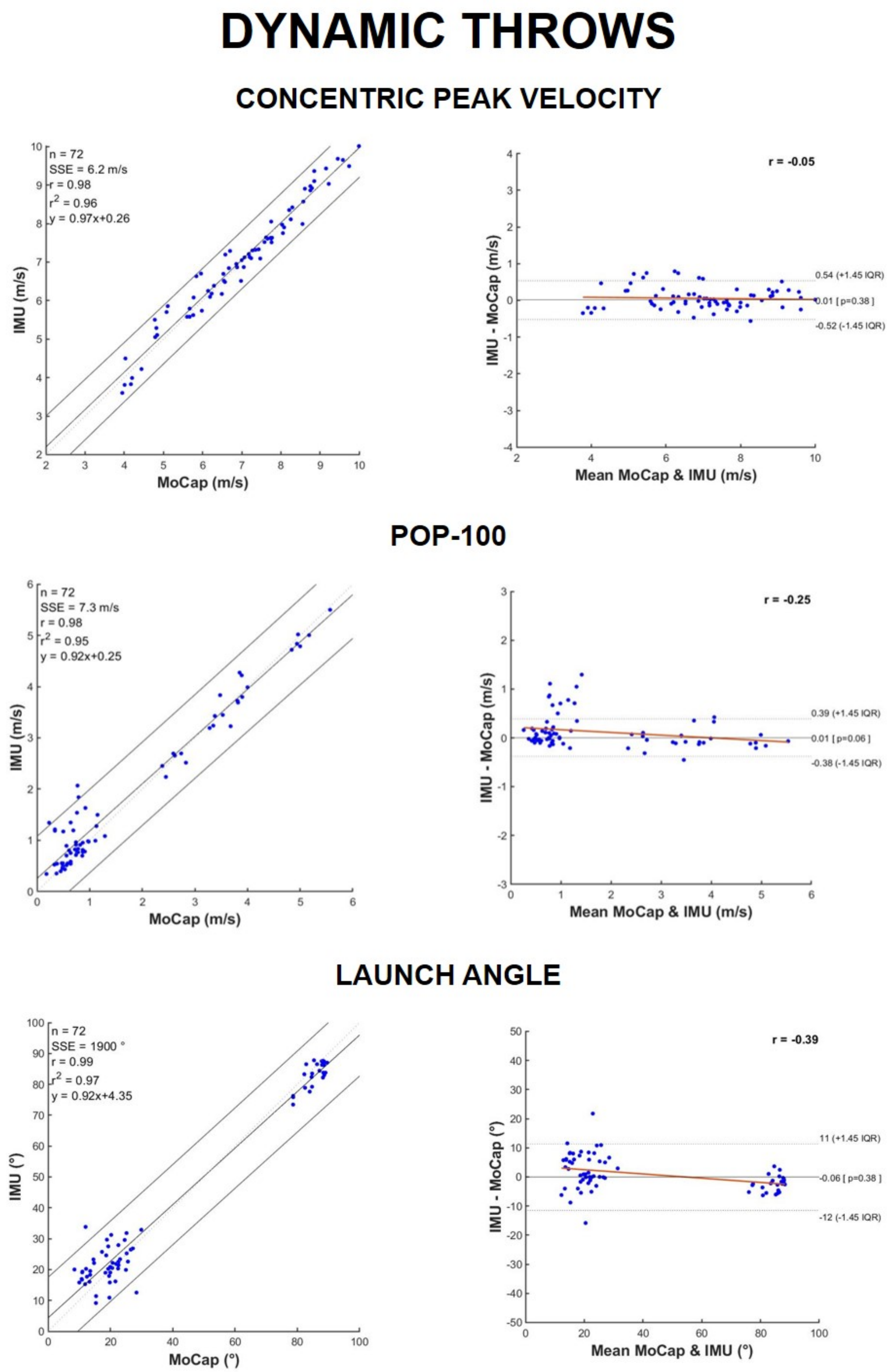

Figure 6. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all dynamic throws performed.

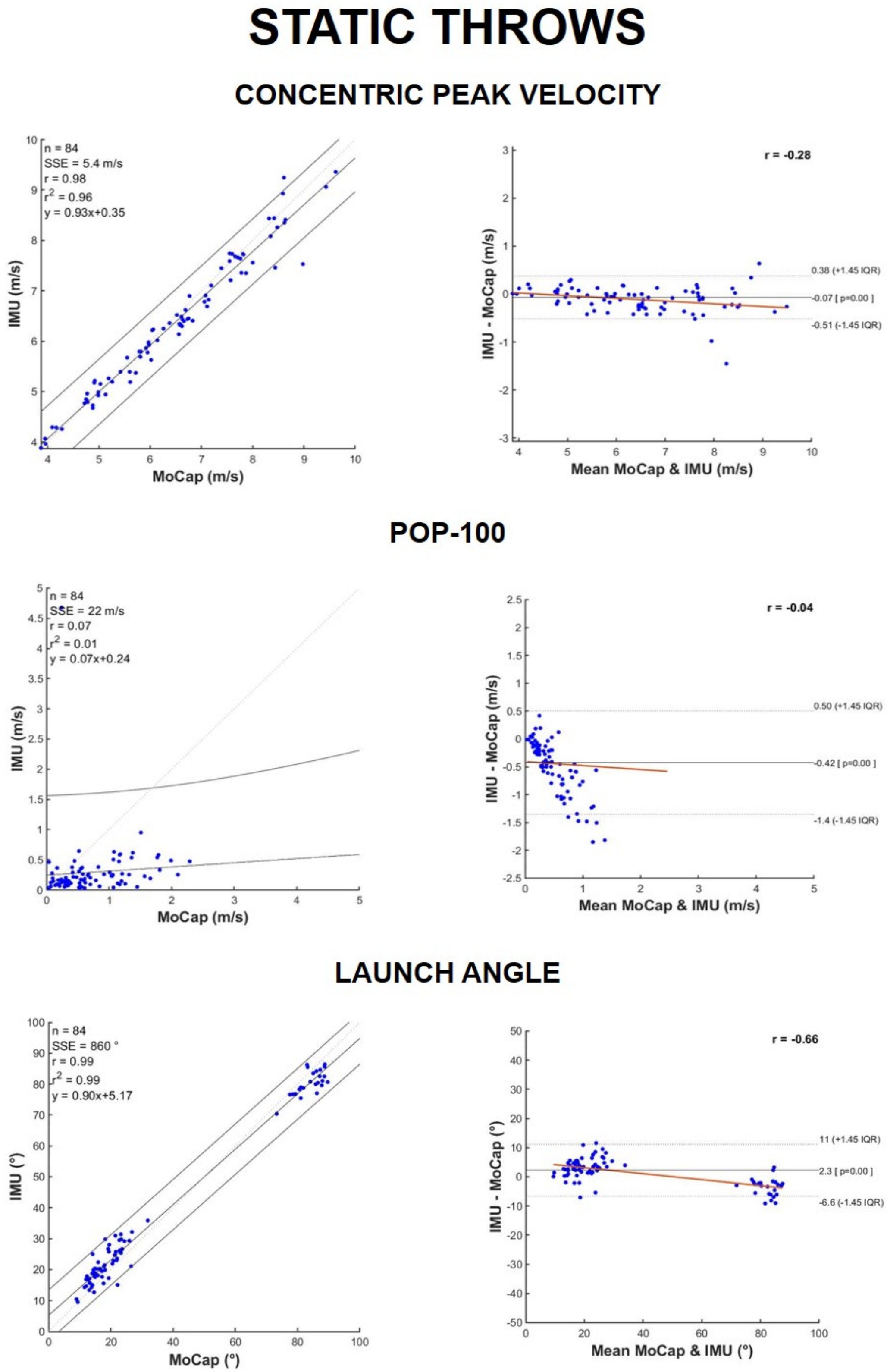

Figure 7. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all static throws performed.

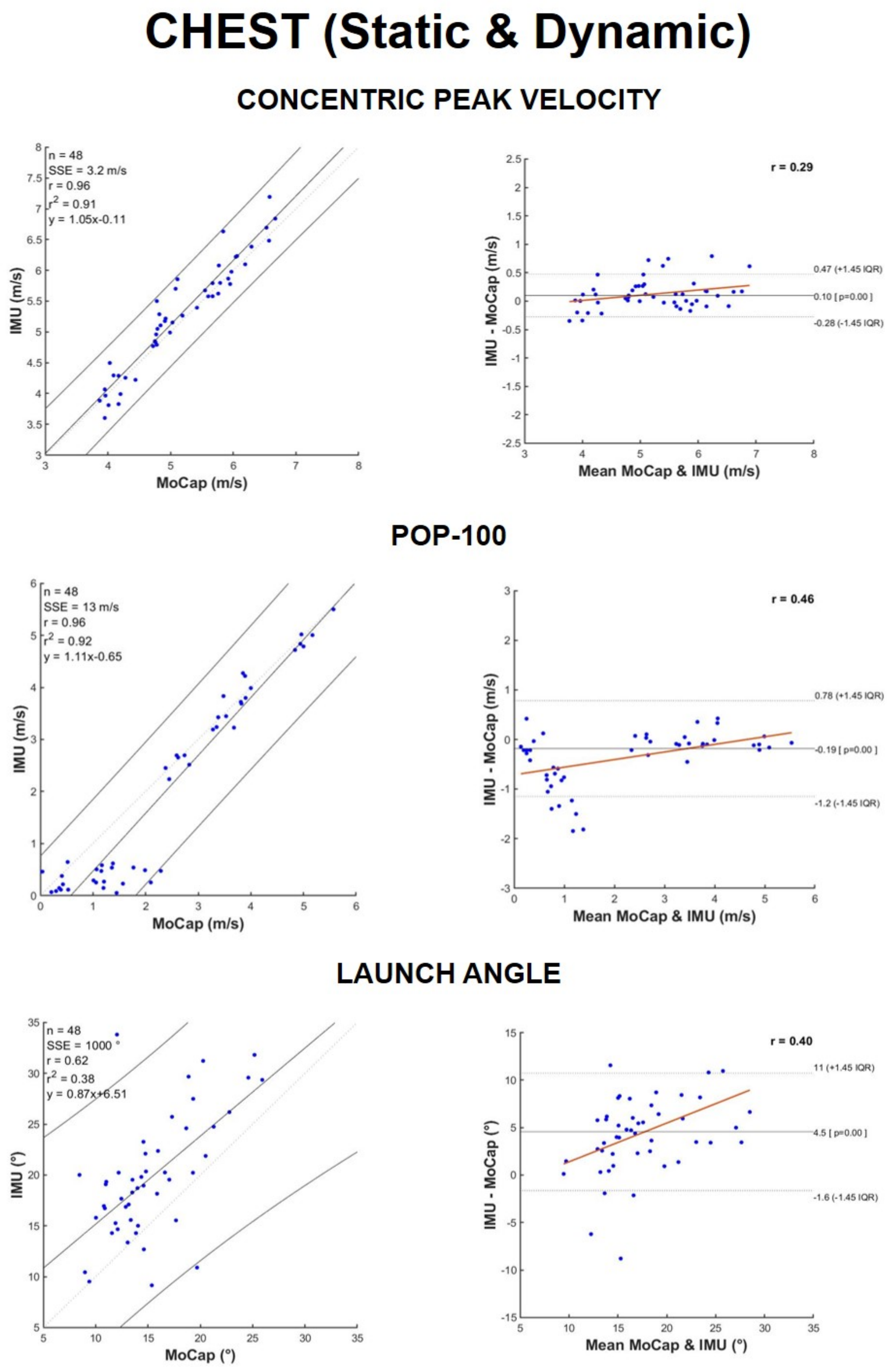

Figure 8. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all chest pass throws performed.

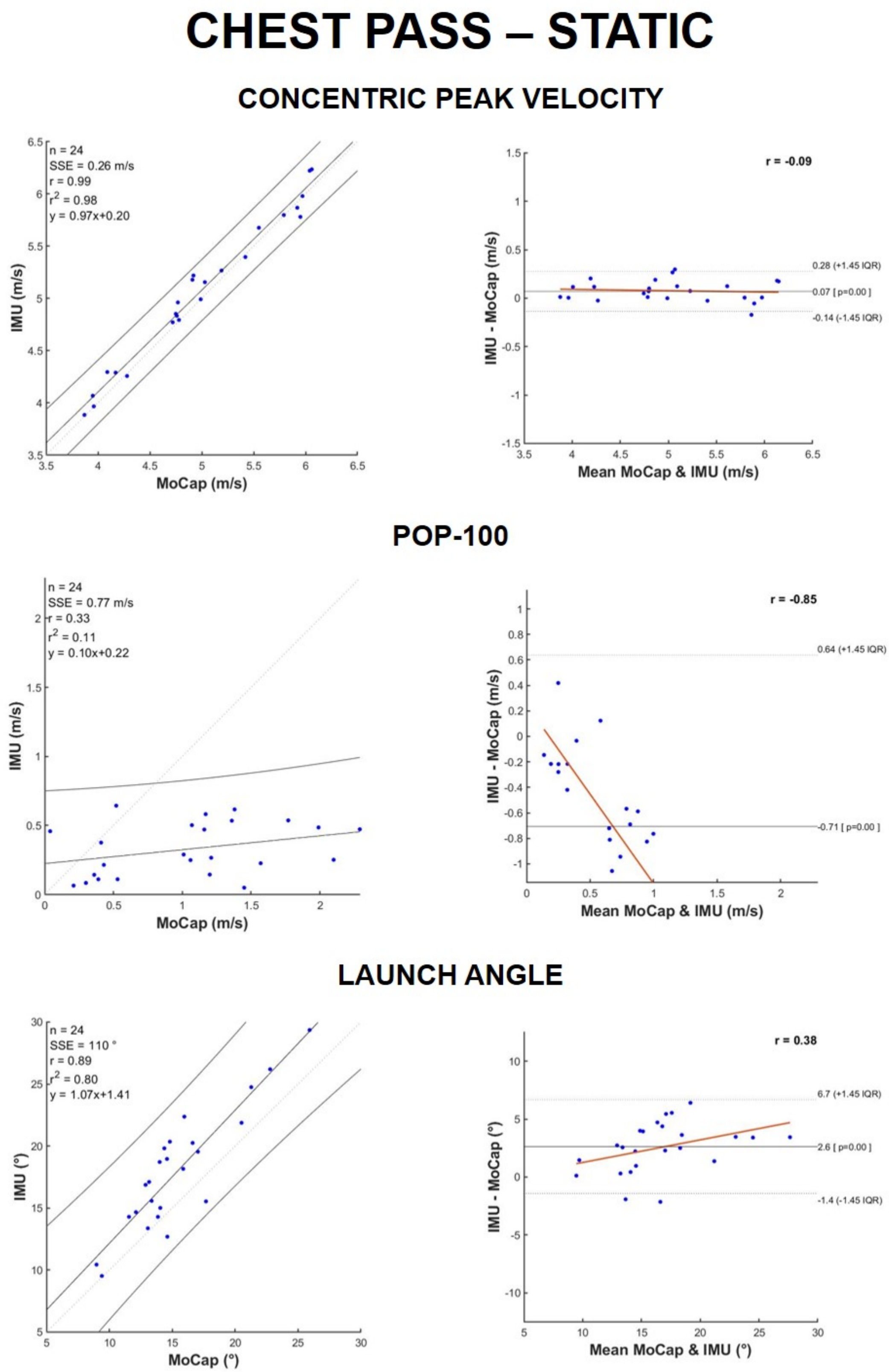

Figure 9. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all chest pass static throws performed.

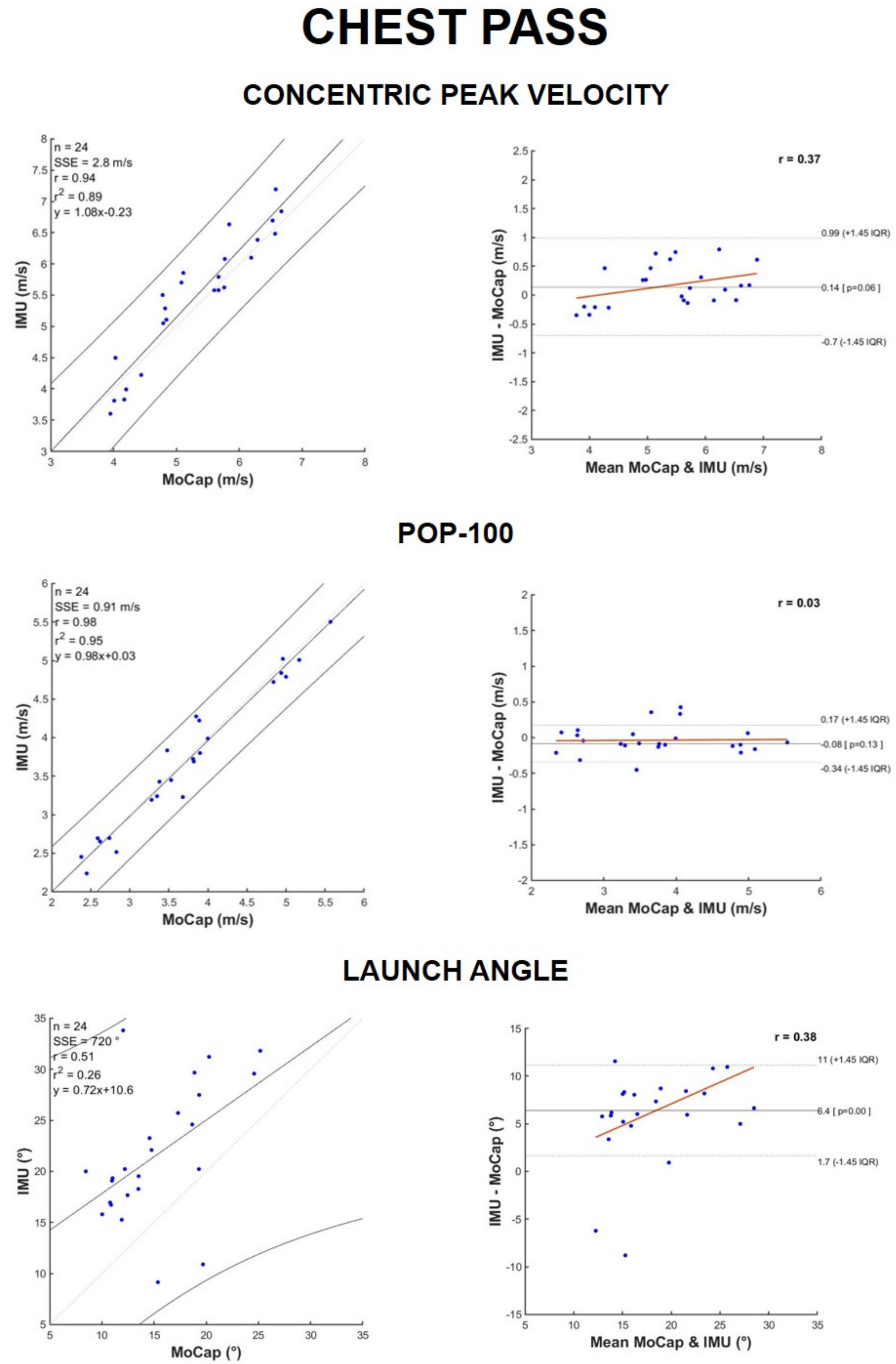

Figure 10. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all chest pass dynamic throws performed.

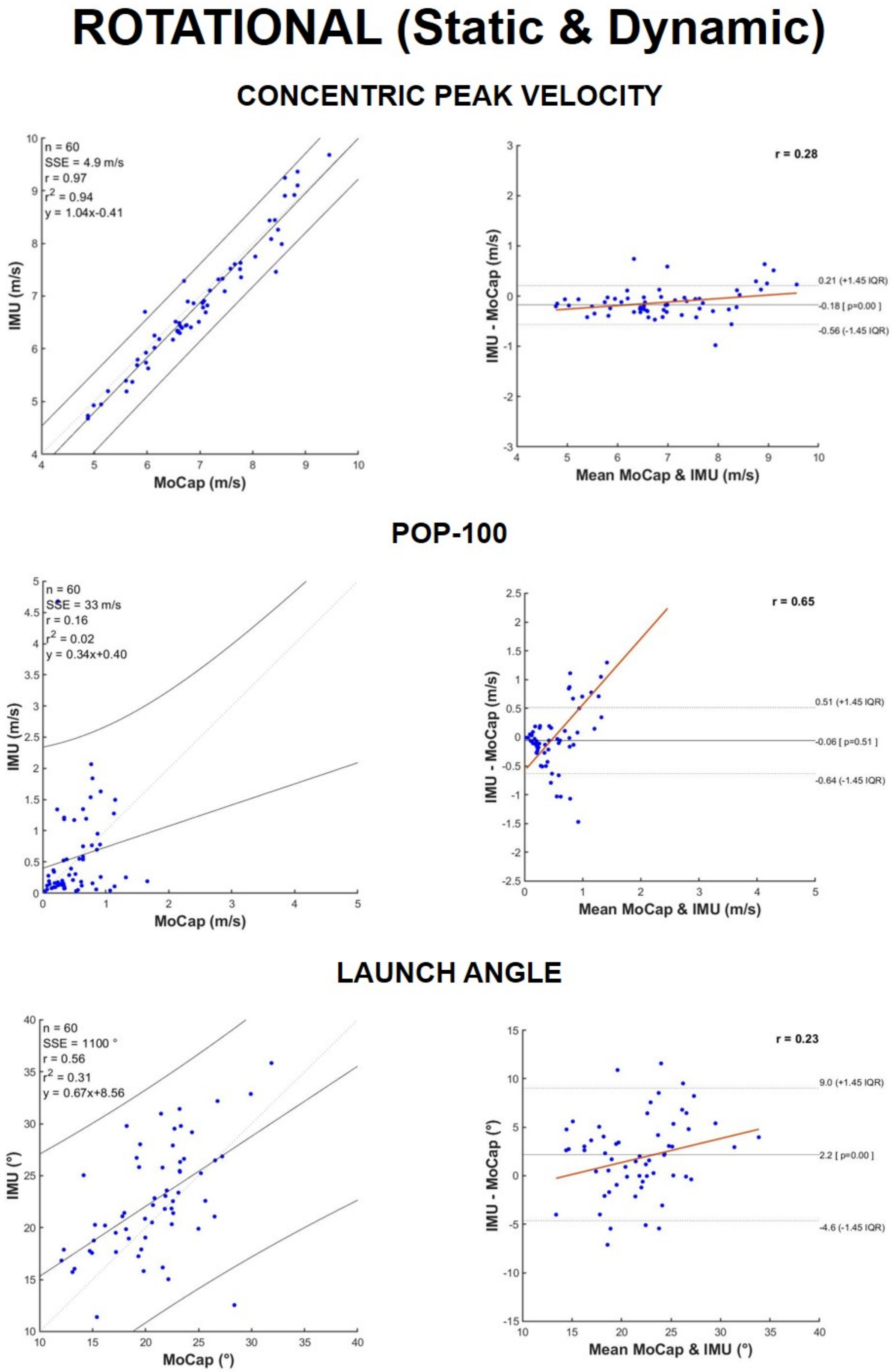

Figure 11. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all rotational throws performed.

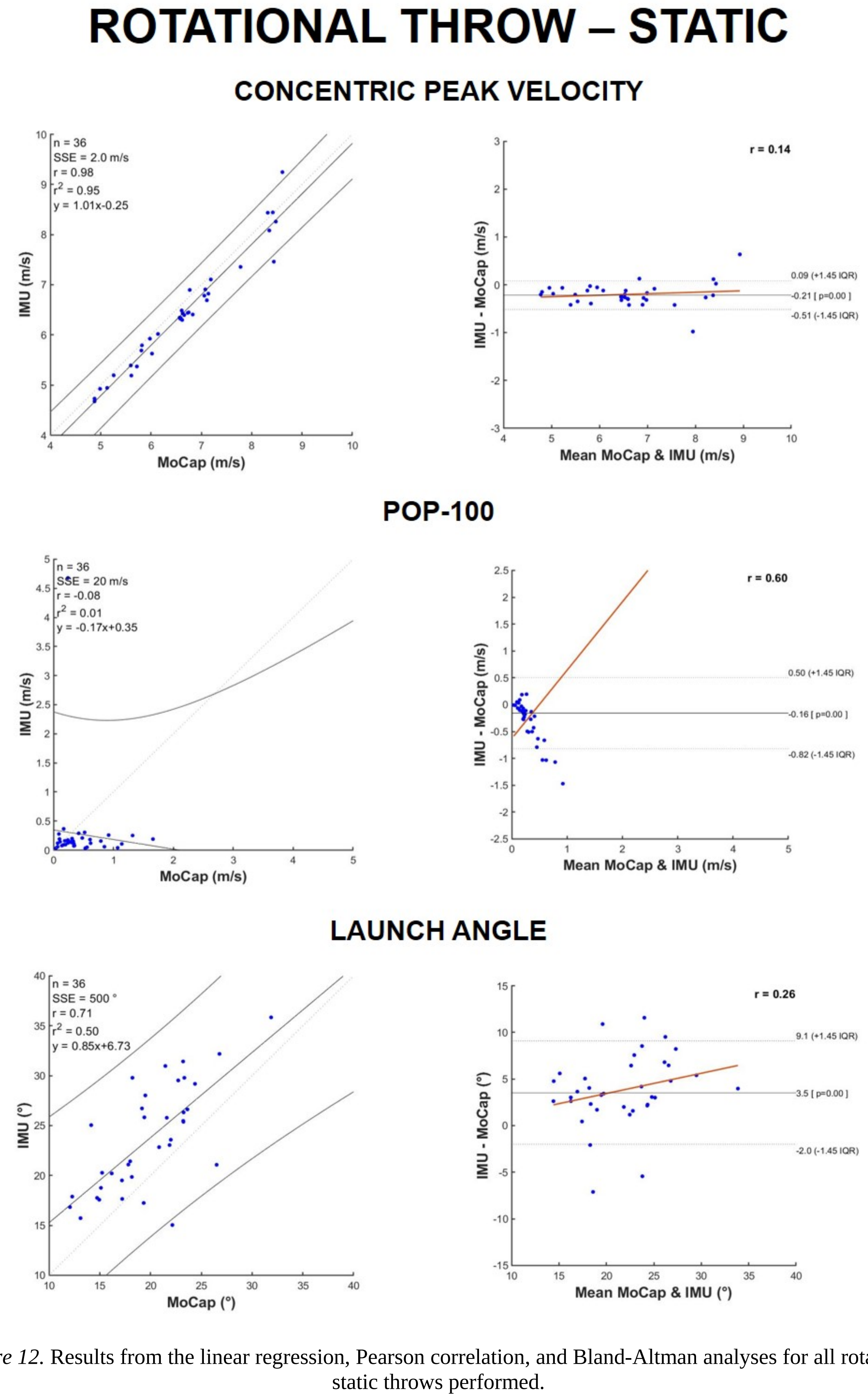

Figure 12. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all rotational static throws performed.

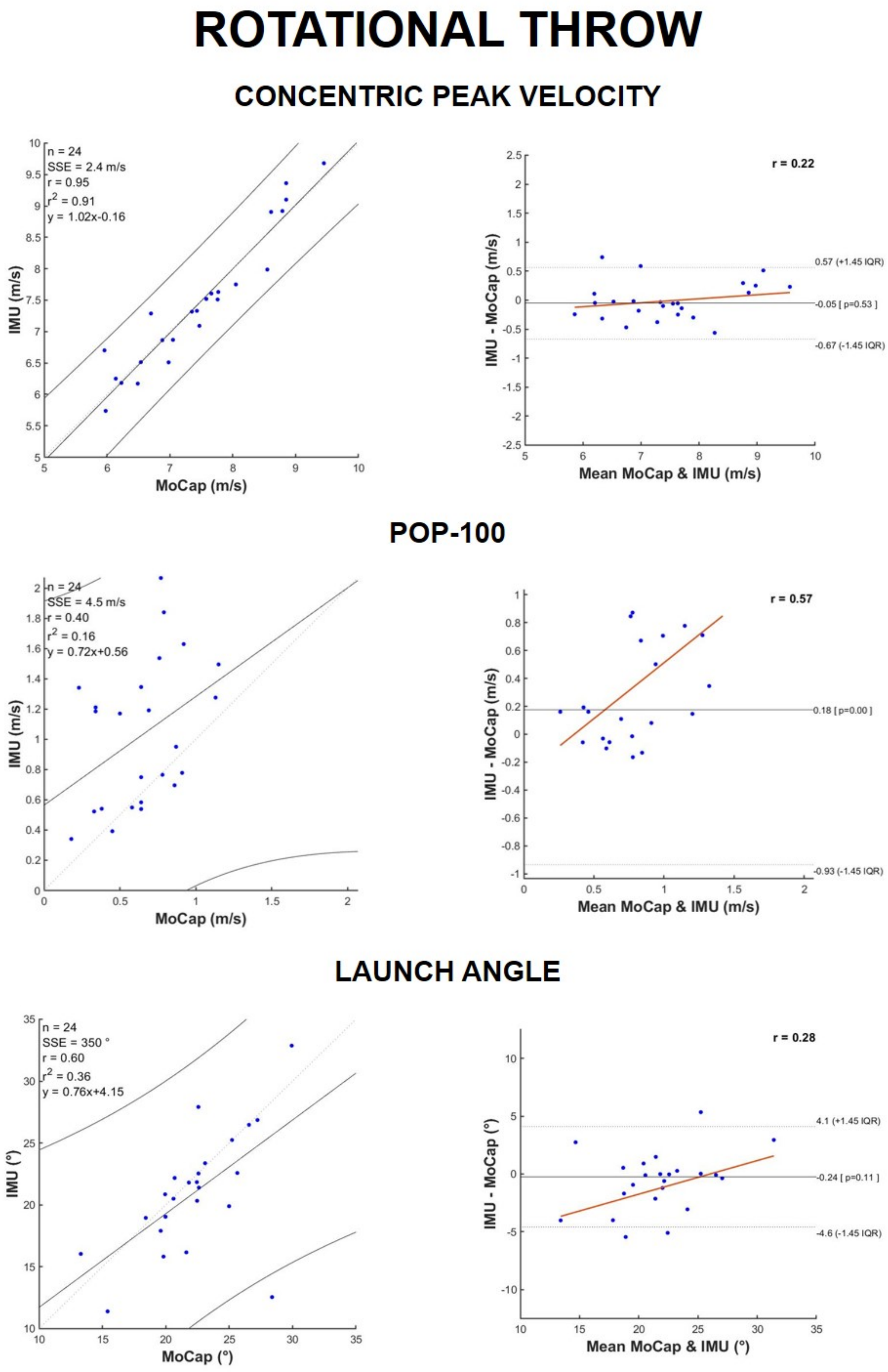

Figure 13. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all rotational dynamic throws performed.

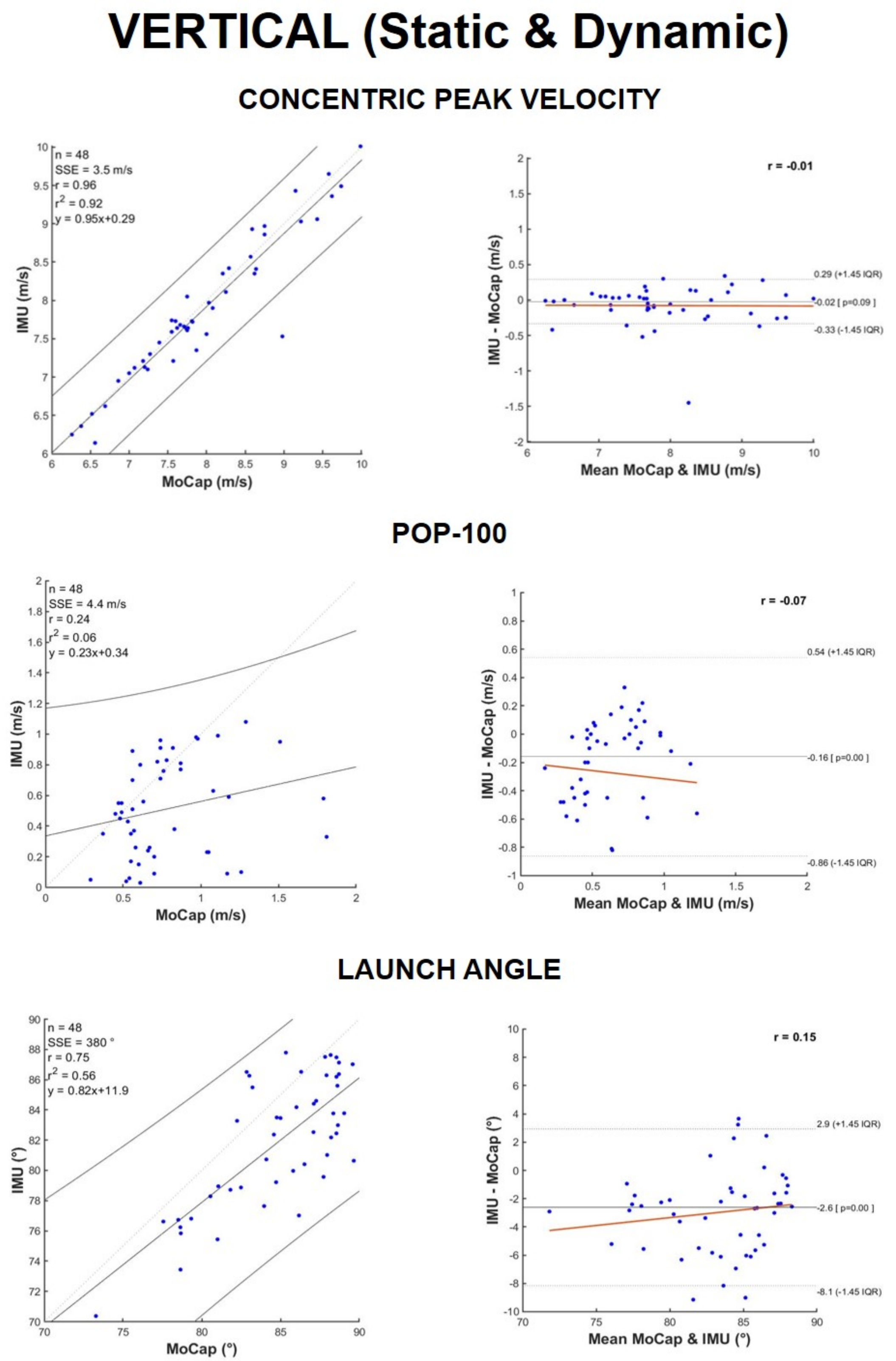

Figure 14. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all vertical throws performed.

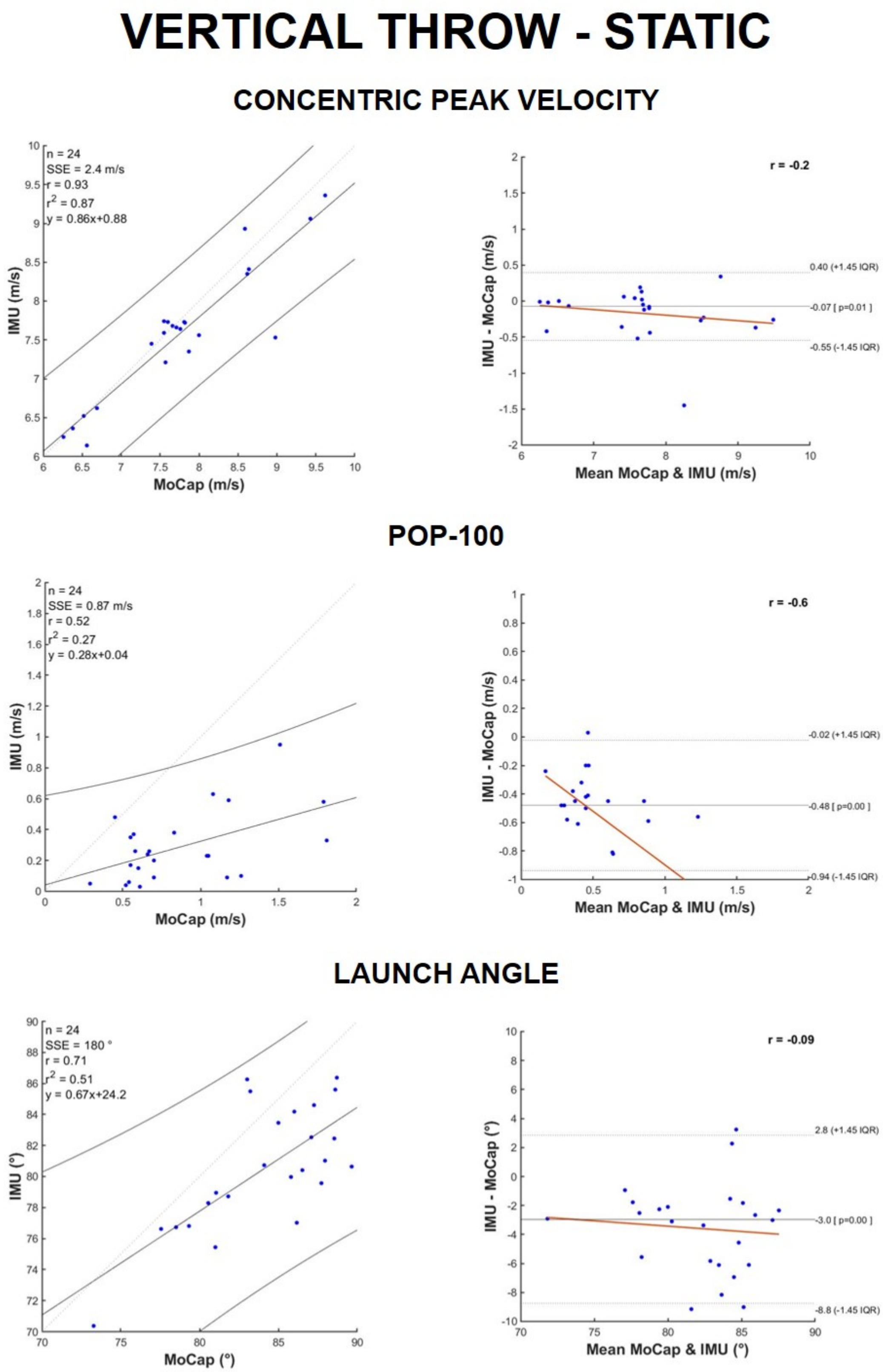

Figure 15. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all vertical static throws performed.

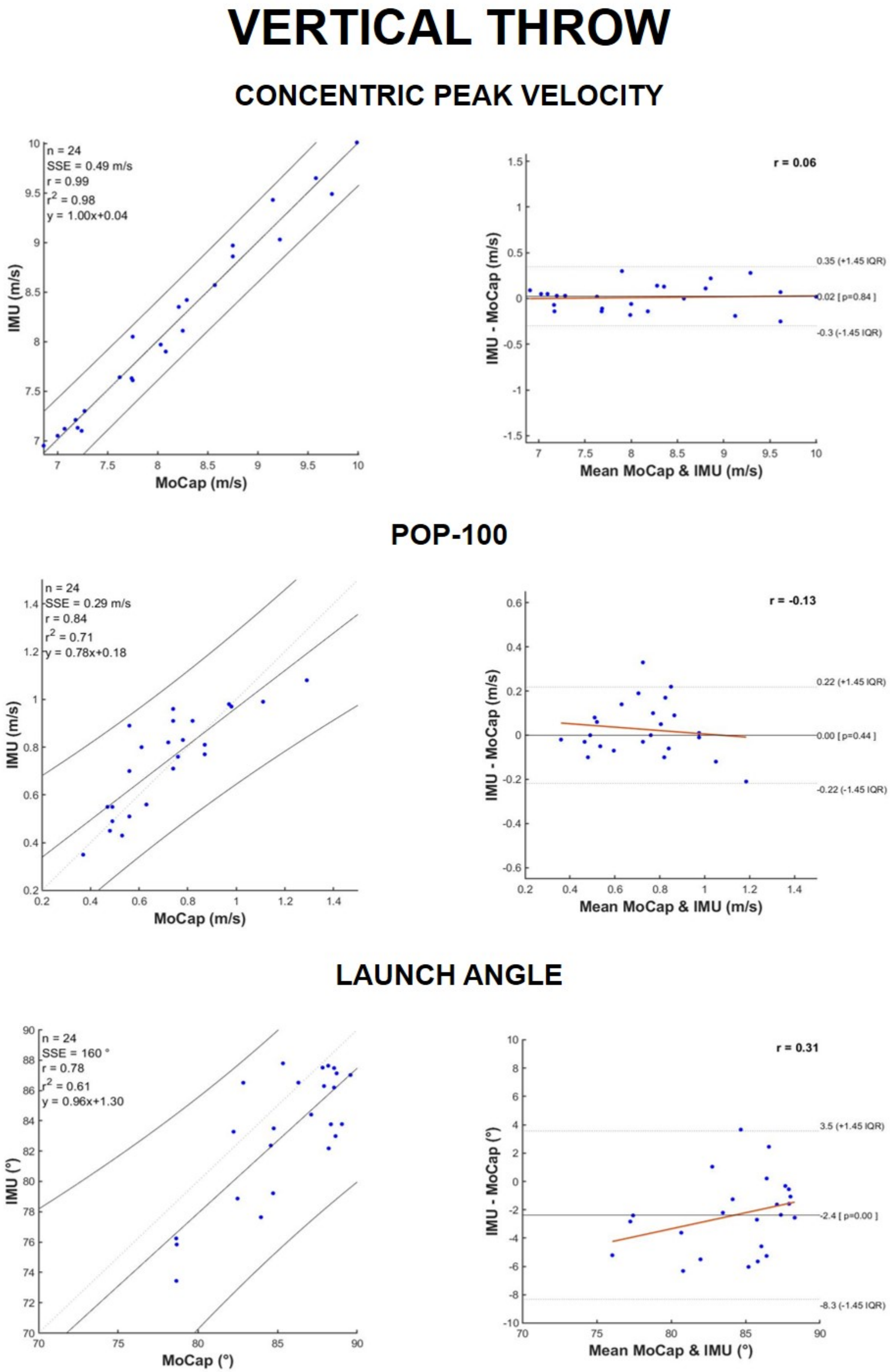

Figure 16. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all vertical dynamic throws performed.