The Validity of a Quaternion-Based Approach to Barbell Tracking

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Table of Abbreviations

Abbreviation	Explanation
VBT	Velocity Based Training
1RM	One Rep Maximum
LPT	Linear Position Transducer
IMU	Inertial Measurement Unit
LCS	Local Coordinate System
GCS	Global Coordinate System
MoCap	3-D Motion Capture
CPV	Concentric Peak Velocity
CMV	Concentric Mean Velocity

Introduction

Resistance training has been employed as a methodology to bring about changes in various muscular characteristics such as size, strength, and power. Traditionally, resistance training programs will vary by altering aspects of the program such as the type of exercises, intensity, and volume with the goal of eliciting a specific muscular response to improve athletic performance. While many of these aspects have been well-studied in the literature, movement velocity has since been brought to the forefront of resistance training research and programming. Measuring the velocity of the barbell during various movements as a means of exercise prescription, or velocity-based training (VBT), is a relatively recent concept with regards to resistance training. While the use of VBT is still debated, this method for monitoring exercise intensity has clear benefits such as a way to normalize intensity across varying training ages, an estimation of an athlete's one-rep maximum (1RM) without demanding maximal tests, and the ability to be monitored within sets as an objective measure of fatigue.

One of the reasons VBT is growing in popularity is due to the increased exposure and accessibility coaches, trainers, and individuals have to products that offer a VBT application. These products typically utilize technologies such as linear position transducers (LPTs), inertial measurement units (IMUs), or smartphone-based video analysis to estimate the velocity of the barbell through various mathematical techniques. The cost of these products varies widely from less than $20 to upwards of $2,000 per unit. Additionally, it has been reported that validity and reliability also range from near-perfect agreement with gold-standard motion capture technology to high degrees of error dependent on the product, movement selection and intensity, and variable of choice. As such, it is critical that any potential customer looking to purchase a product with a

VBT application understands the accuracy and precision with which that product reports the metrics a customer is interested in.

Products such as FIT7502's original Bar Sensei utilize an IMU to collect acceleration and rotation data of the barbell during various exercises which can be used to estimate velocity, position, force, and power of the movement. While IMUs have clear benefits such as cost (compared to other technologies) and portability, they are not without their limitations. Namely, IMUs are prone to noise and drift that may be attenuated through prolonged use, as well as the fact that the unit measures acceleration and gyroscopic data in a local coordinate system (LCS). This causes challenges interpreting barbell mechanics in the global reference frame, particularly when the bar undergoes excessive rotation during a movement. A mathematical transformation of IMU data utilizing quaternion algebra and specific filtering may be implemented as a solution to the previously stated problems, which offers the representation of IMU data in the global coordinate system (GCS) rather than the LCS. Once transformed, this data can be used to describe barbell acceleration in all three primary axes of the GCS where linear velocity and position can then be estimated with more relevance to the VBT application. However, the data extracted from this method within the Bar Sensei IMU has yet to be validated. Therefore, the purpose of this investigation was to explore the validity of various VBT metrics calculated from the FIT7502 IMU using a quaternion-based algorithm when compared to the gold-standard of 3-D motion capture technology across a variety of commonly prescribed resistance training exercises.

Methods

IMU Algorithm

The algorithm was developed for use in the FIT7502 family of hardware products and mobile applications. The goal of the algorithm is to take the raw data exported from the IMU and transform the data such that it can be represented in the global coordinate system and interpreted for barbell tracking uses. This method is intended to support existing Bar Sensei IMUs as well as the next generation of hardware estimated to launch in the middle of 2021.

Participants

Data was collected from four healthy participants familiar with resistance training and the exercises performed (mean ± SD; age: 28.3 ± 3.6 years, weight: 201.3 ± 21.4 lbs, height: 71.6 ± 4.0 inches). The training experience varied between the participants with one being classified as a novice weightlifter, two being recreational (non-competitive) weightlifters, and one participant who competed regularly in weightlifting competitions. The sample was thought to represent a randomly selected sample of customers who may use VBT technology in their training. The sample was also restricted to availability of participants on the day of testing. All participants were familiarized with the testing protocol and technology prior to data collection.

Equipment

All data was collected in an exercise facility outfitted with conventional resistance training equipment including barbell squat racks, power lifting platforms, and adjustable training benches. FIT7502 IMU data was collected from a singular module fixed to the barbell in accordance with the manufacturer's guidelines. Optical motion capture (MoCap) was used simultaneously to collect 3D positional data with four motion capture cameras (Oqus 7+, Qualisys AB, Sweden) operating at the same frequency as the IMU. The capture volume was calibrated prior to all data collection sessions with a measurement error of <1.0mm accepted. A single retroreflective marker was placed directly on the IMU on the outside of the sleeve provided by the manufacturer such that the reference point from which measurements were output from the IMU and motion capture system did not differ in location.

Data Collection

The data collection consisted of measurements recorded for five different barbell exercises commercially available in the FIT7502 mobile application: squat, bench press, squat jump, deadlift, and power/hang clean. For the squat, two participants completed 6 repetitions per intensity for three separate intensities (30, 60, and 90% 1RM, Table 1). For the bench press, one participant completed 6 repetitions per intensity for all three intensities. For the squat jump, two participants completed 6 repetitions per intensity for the lowest two intensities. For the power clean, two participants completed 6 repetitions per intensity for the two lowest intensities, while only one completed 6 repetitions at the highest intensity. The participant who did not complete the power clean at the highest intensity instead completed 6 repetitions of hang clean at the middle intensity (60% 1RM). One participant completed two sets of 6 repetitions each for the deadlift for the lowest two intensities, followed by 6 repetitions at the highest intensity. Participants were allowed adequate rest between reps and sets. A representation of the testing matrix is provided in Table 1. A total of 144 repetitions were collected for analysis. All exercises were performed in accordance with the manufacturer's recommendations for valid IMU data collection.

Table 1. Testing matrix for data collection.

Movement	Squat	Bench Press	Squat Jump	Power/Hang Clean	Deadlift
Participants	n = 2	n = 1	n = 2	n = 2	n = 1
Intensities (% 1RM)	30, 60, 90	30, 60, 90	30, 60	30, 60, 90	30, 60, 90
Total Reps	36	18	24	36	30
Variables Recorded	CPV POP-100™ Distance	CPV POP-100™ Distance	CPV POP-100™ Distance	CPV CMV Distance	CPV CMV

CPV = Concentric Peak Velocity; CMV = Concentric Mean Velocity

Data Processing

Three repetitions, two from the power clean and one from the hang clean exercise, were removed due to obvious internal error (distance measurement less than half the expected outcome) from the IMU output data in the application. All other trials were used for analysis. Motion capture data was processed for the duration of each repetition for all movements. Raw position data of the marker was then exported from the motion capture software to Visual 3D (C-Motion, Germantown, MD) for analysis. The position data 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 was then derived to obtain velocity and acceleration data for all trials collected. Variables corresponding to those present in Table 1 were then calculated in Visual 3D. Concentric peak velocity (CPV) was calculated as the peak linear velocity of the barbell in the vertical direction during the concentric phase of the lift. POP-100™, a proprietary variable of FIT7502, was calculated as the instantaneous vertical velocity of the barbell at the 100 millisecond point of the concentric phase of the lift. Concentric mean velocity (CMV) was calculated as the arithmetic mean of the barbell velocity in the vertical direction throughout the duration of the concentric portion of the lift. Distance was calculated as the difference in vertical position of the barbell from the start of the lift to the end of the eccentric phase for the case of squat, bench press, and squat jump. Distance for the power clean was calculated as the difference of vertical position of the barbell from the beginning of the movement to the completed catch. All calculated variables were then exported and used for analysis. The same variables output from the company's mobile 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 relative intensity for each exercise. Data was assessed in groups based on exercise, intensity, and as a whole. A series of analysis of variance (ANOVA) tests were used to determine differences between devices as well as the effect of the device, exercise performed, intensity, and potential interaction effects. ANOVA tests were performed for each variable. To assess the between device agreement, a combination of Pearson's correlation, linear regression, and Bland-Altman analyses were applied to each of the variables in each respective group. 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, at each intensity, and for each variable between each system are provided in Table 2. The series of ANOVA tests revealed no significant differences between devices for CPV, POP-100^{TM}, and Distance with no significant interaction of devices for both exercises and intensities. CMV was significantly affected by the interaction of the device ($F = 4.00$, $p < 0.05$) and intensity as well as by the interaction of the device and exercise ($F = 8.5$, $p < 0.01$); Bonferroni *post hoc* analysis revealed significant differences between devices, $p < 0.05$. Simple main effects revealed a significant difference for CMV between devices for the case of the power clean exercise at low intensities ($p < 0.05$, Table 2). Linear regression, Bland-Altman, and Pearson statistics for each movement and each variable as well as for all movements all intensities and all variables can be found in the Appendix.

When considering all intensities and all movements, a nearly perfect relationship existed between devices for CPV, POP-100^{TM}, Distance, and CMV, $r=0.99$, $r=0.99$, $r=0.98$, $r=0.95$, respectively. Bland-Altman analysis across all intensities for all movements indicated no bias for CPV, POP-100^{TM}, Distance, or CMV across devices. When evaluating CPV at the various intensities, a near perfect relationship existed between devices at 30, 60, and 90% 1RM, $r=0.99$, $r=0.99$, $r=0.99$, respectively. Bland-Altman analysis revealed no significant bias between devices for CPV at each intensity.

For the squat exercise only, a near perfect relationship existed between devices for CPV and POP-100^{TM} across all intensities, r=0.98 and r=0.96 respectively. A very large correlation existed between devices for Distance measured in the squat, r=0.80. Bland-Altman analysis revealed no significant bias between devices for the CPV and POP-100^{TM} variables measured in the squat exercise across all intensities. Significant bias ($p < 0.05$) was present between devices for Distance measured in the squat with the IMU over-reporting Distance by 0.01 meter on average.

For the bench exercise only, a near perfect relationship existed between devices for CPV and POP-100^{TM} across all intensities, r=0.98 and r=0.97 respectively. A large correlation was present for the case of Distance measured in the bench, r=0.61. Bland-Altman analysis revealed no significant bias between devices for the CPV and POP-100^{TM} variables measured in the bench exercise across all intensities. Significant bias ($p < 0.05$) was present between devices for Distance measured in the bench with the IMU over-reporting Distance by 0.01 meter on average.

For the squat jump exercise only, a near perfect relationship existed between devices for CPV, POP-100^{TM}, and Distance across all intensities, r=0.97, r=1.00, and r=0.91, respectively. Bland-Altman analysis revealed no significant bias between devices for the CPV and POP-100^{TM} variables measured in the squat jump exercise across all intensities. Significant bias ($p < 0.01$) was present between devices for Distance measured in the squat jump with the IMU over-reporting Distance by 0.02 meter on average.

For the power and hang clean exercises only, a very large correlation existed between devices for CPV across all intensities, r=0.86. A near perfect relationship existed between devices for Distance measured across all intensities in the power and hang clean exercises, r=0.94. A moderate correlation was present for the case of CMV measured in the power and hang cleans,

$r=0.46$. Bland-Altman analysis revealed no significant bias between devices for the CPV measured in the power and hang clean exercises across all intensities. Significant bias ($p < 0.05$) was present between devices for CMV measured in the power and hang clean exercises with the IMU over-reporting CMV by 0.06 meters per second on average. Significant bias ($p < 0.05$) was present between devices for Distance measured in the power and hang clean exercises with the IMU under-reporting Distance by 0.03 meters on average.

For the deadlift exercise only, a near perfect relationship existed between devices for CPV and CMV across all intensities, $r=0.95$ and $r=0.94$ respectively. Bland-Altman analysis revealed no significant bias between devices for CMV measured in the deadlift exercise across all intensities. Significant bias ($p < 0.01$) was present between devices for CPV measured in the deadlift with the IMU under-reporting CPV by 0.11 meters per second on average.

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

Exercise	Trials (n)	Intensity (% 1RM)	Device	CPV (m/s)	POP-100™ (m/s)	Distance (m)	CMV (m/s)
Squat	12	30	IMU MoCap	1.32 ± 0.48 1.30 ± 0.45	0.48 ± 0.05 0.46 ± 0.04	0.61 ± 0.03 0.62 ± 0.03	- -
	12	60	IMU MoCap	1.22 ± 0.39 1.20 ± 0.37	0.41 ± 0.03 0.41 ± 0.04	0.61 ± 0.05 0.61 ± 0.04	- -
	12	90	IMU MoCap	1.06 ± 0.42 1.13 ± 0.35	0.27 ± 0.04 0.28 ± 0.03	0.60 ± 0.03 0.58 ± 0.02	- -
	36	Full	IMU MoCap	1.20 ± 0.43 1.21 ± 0.39	0.39 ± 0.10 0.38 ± 0.09	0.61 ± 0.04 0.60 ± 0.03	- -
Bench	6	30	IMU MoCap	0.86 ± 0.05 0.86 ± 0.03	0.45 ± 0.03 0.44 ± 0.03	0.37 ± 0.01 0.37 ± 0.01	- -
	6	60	IMU MoCap	0.48 ± 0.08 0.50 ± 0.03	0.25 ± 0.03 0.26 ± 0.02	0.36 ± 0.03 0.34 ± 0.01	- -
	6	90	IMU MoCap	0.36 ± 0.09 0.41 ± 0.05	0.17 ± 0.05 0.20 ± 0.02	0.35 ± 0.04 0.32 ± 0.01	- -
	18	Full	IMU MoCap	0.57 ± 0.23 0.59 ± 0.20	0.29 ± 0.13 0.30 ± 0.11	0.36 ± 0.03 0.34 ± 0.02	- -
Squat Jump	12	30	IMU MoCap	2.19 ± 0.20 2.17 ± 0.21	0.66 ± 0.33 0.66 ± 0.34	0.64 ± 0.04 0.63 ± 0.04	- -
	12	60	IMU MoCap	1.94 ± 0.09 1.93 ± 0.07	0.50 ± 0.22 0.49 ± 0.22	0.61 ± 0.05 0.59 ± 0.05	- -
	24	Full	IMU MoCap	2.07 ± 0.20 2.05 ± 0.20	0.58 ± 0.29 0.57 ± 0.29	0.63 ± 0.05 0.61 ± 0.05	- -
Power/Hang Clean	12	30	IMU MoCap	2.44 ± 0.16 2.44 ± 0.20	- -	1.16 ± 0.07 1.20 ± 0.02	1.32 ± 0.09 1.19 ± 0.13
	16	60	IMU MoCap	2.14 ± 0.19 2.17 ± 0.13	- -	0.91 ± 0.29 0.97 ± 0.25	1.24 ± 0.08 1.26 ± 0.11
	5	90	IMU MoCap	1.97 ± 0.11 1.86 ± 0.06	- -	1.16 ± 0.10 1.10 ± 0.06	1.09 ± 0.04 0.96 ± 0.09
	33	Full	IMU MoCap	2.22 ± 0.24 2.22 ± 0.25	- -	1.04 ± 0.24 1.07 ± 0.20	1.24 ± 0.11 1.19 ± 0.15
Deadlift	12	30	IMU MoCap	1.42 ± 0.12 1.53 ± 0.08	- -	- -	0.73 ± 0.05 0.75 ± 0.05
	12	60	IMU MoCap	0.90 ± 0.13 1.02 ± 0.06	- -	- -	0.50 ± 0.05 0.53 ± 0.03
	6	90	IMU MoCap	0.64 ± 0.07 0.70 ± 0.03	- -	- -	0.36 ± 0.05 0.34 ± 0.04
	30	Full	IMU MoCap	1.06 ± 0.34 1.16 ± 0.34	- -	- -	0.56 ± 0.15 0.58 ± 0.16

MoCap = Qualisys Motion Capture system; CPV = Concentric Peak Velocity; CMV = Concentric Mean Velocity; Full = all trials recorded for a given exercise.

Discussion

The purpose of this investigation was to explore the validity of a quaternion-based algorithm for measuring VBT metrics of importance in a commercially available wireless IMU product across a variety of movements and intensities. The results from this investigation indicate that the algorithm is valid for measuring CPV, POP-100^{TM}, Distance, and CMV across the squat, bench, squat jump, power and hang clean, and deadlift exercises at a range of intensities. Overall, the devices were in agreement with no presence of bias for any variables reported across all trials. A trend was exhibited in the Bland-Altman analysis for bias in CPV across all trials ($p = 0.07$) indicating that the IMU may under-report CPV at higher intensities and may over-report CPV at lower intensities. Further investigation into CPV at trials recorded only at 90% intensity revealed a mean difference of -0.03 meters per second between devices indicating that at the highest intensities the IMU under-reported CPV, however, no statistical significance was observed in this trend ($p = 0.07$). No bias was observed between devices for CPV at either of the other two intensities. These results indicate that as intensity increases, no statistically significant bias was introduced into the IMU for measure of CPV, making CPV a valid measure for any of the exercises investigated at any intensity.

The weakest correlation observed was for the case of the power and hang clean exercises measuring CMV ($r = 0.46$). Significant bias was also observed with the IMU over-estimating CMV at higher intensities and under-estimating CMV at lower intensities ($p = 0.04$). These results indicate that CMV may not be a valid measure in the power and hang clean exercises with the current algorithm-IMU tandem. However, CPV and Distance measurements exhibited very good agreement between devices with the presence of significant, but small bias for the case of Distance. These findings demonstrate that CPV and Distance may be valid measurements during the power and hang clean exercises, but not CMV for the case of the current product.

The best agreement between devices was observed for the CPV and POP-100^{TM} metrics in the squat, squat jump, and bench exercises. Near perfect agreement was observed for both metrics across all three exercises for all intensities with no presence of significant bias. These results indicate the current product is valid for measuring CPV or POP-100^{TM} in the squat, bench, or squat jump exercise.

Agreement between devices was near-perfect when evaluating all four variables (CPV, POP-100^{TM}, Distance, and CMV) across all trials collected. These results indicate that the algorithm is an accurate and unbiased solution for use in an IMU to measure VBT metrics. Additionally, it has been previously reported that many IMU products measuring VBT characteristics, such as CPV and CMV, lose accuracy and introduce bias as intensities increase which was not the case for the IMU employing the current algorithm. Comparing these results loosely to previous studies assessing the validity of various IMU products, the current algorithm-IMU combination employed in this investigation would outperform many other commercially available products in the case of CPV in the squat with regards to data quality.

This investigation is not without limitations. Specifically, not all exercises offered by the IMU's mobile application were examined. Previous studies examining the validity of VBT products commonly evaluate exercises such as the squat, bench press, and clean variations for their analysis, which were all examined in the current investigation. Additionally, a relatively small number of repetitions were collected 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 intensities to assess the validity of the device with greater confidence. Only a small number of VBT metrics were analyzed for validity of the product even though the smartphone application allows a user to collect many additional metrics. While not every VBT metric available was analyzed, the metrics chosen for analysis were those similar to previous studies assessing VBT devices for validity, including CPV and CMV. Further, 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. Additional research is needed to prove the veracity of these claims, however.

Conclusion

The purpose of this investigation was to assess the validity of a newly developed algorithm for IMU-based barbell tracking for the purpose of velocity-based training. Results from this investigation suggest that the algorithm-IMU product provides valid measurements of CPV, POP-100™, Distance, and CMV across a spectrum of loads and exercises. Specifically, across all trials and intensities, near perfect agreement between the IMU and gold-standard motion capture system was observed for all variables measured with no presence of significant bias. Future development is warranted to more accurately assess CMV in the power and hang clean exercises, however, the results from this investigation indicate that the data from the IMU is valid for any of the other investigated VBT applications.

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Appendix

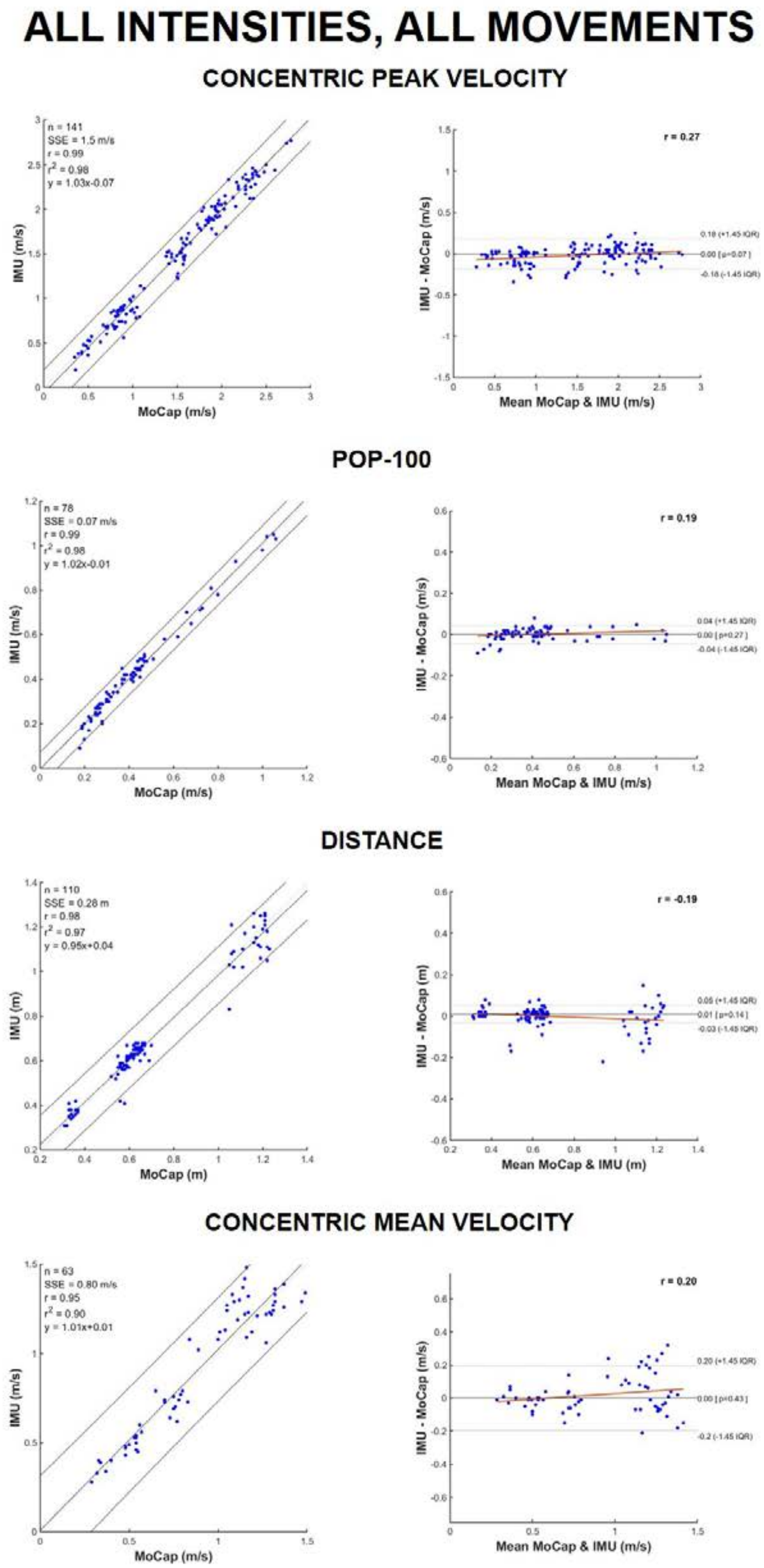

Figure 1. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all metrics recorded across all trials.

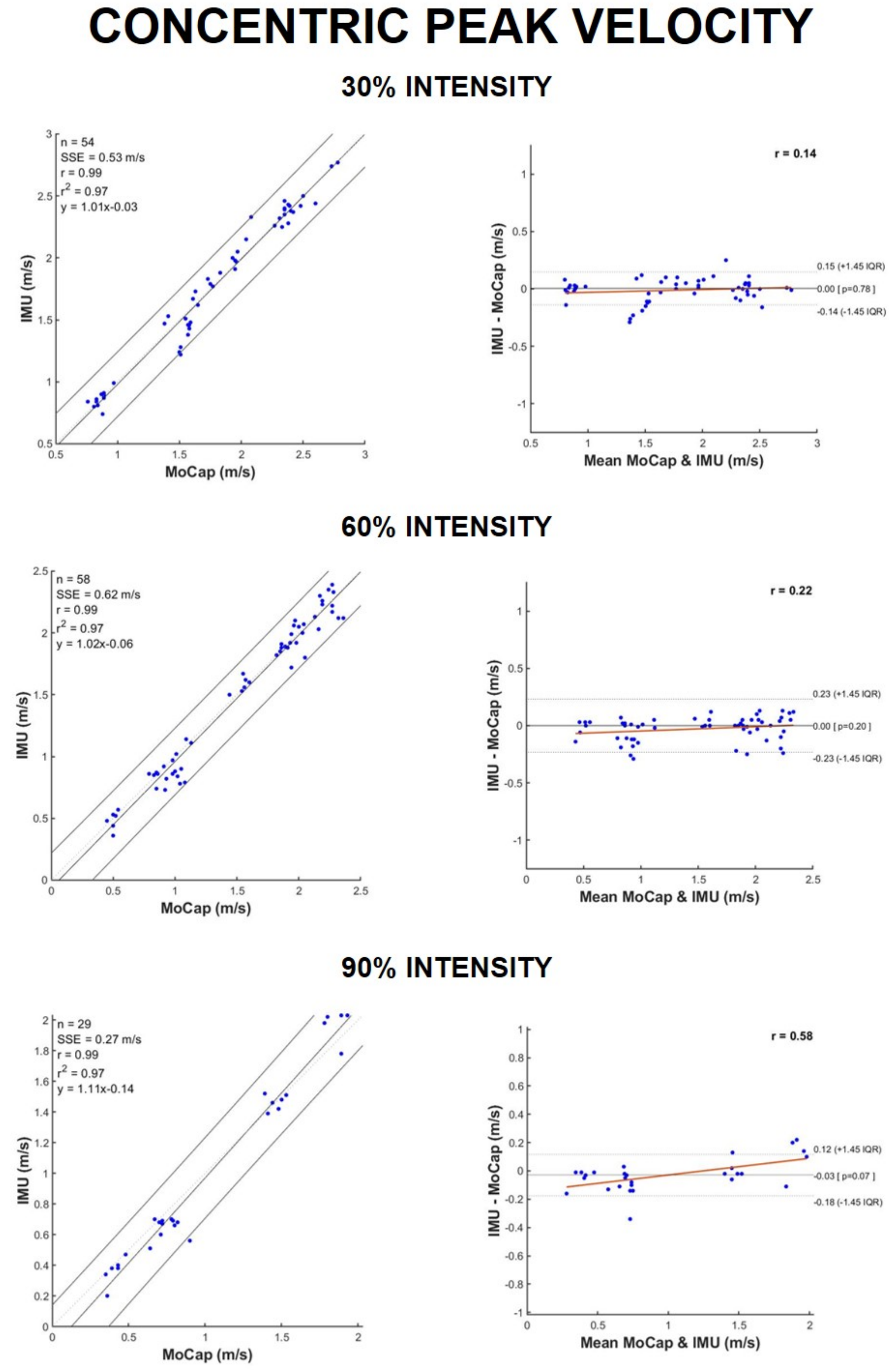

Figure 2. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for CPV at each intensity.

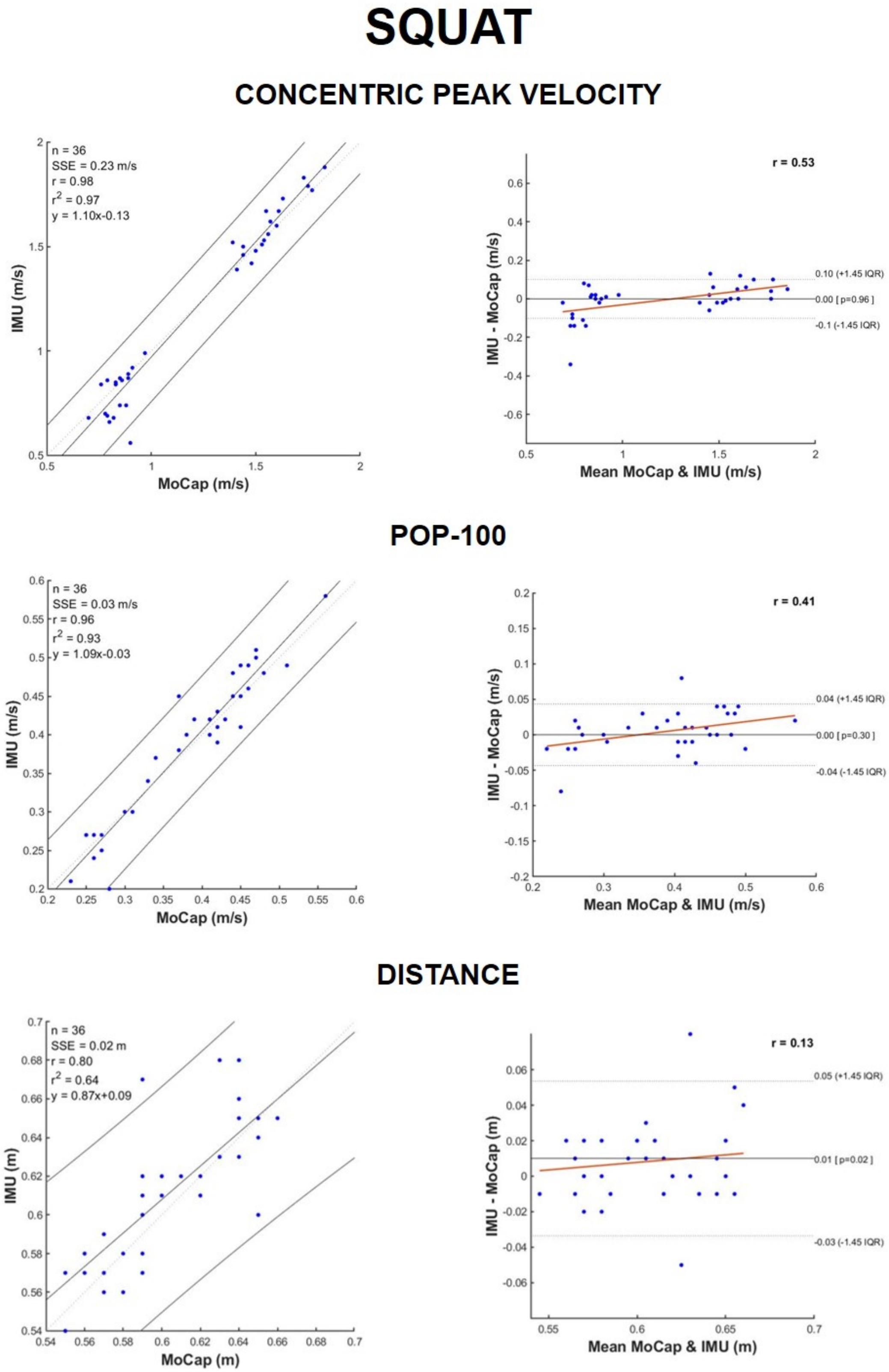

Figure 3. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all metrics recorded across all intensities for the squat.

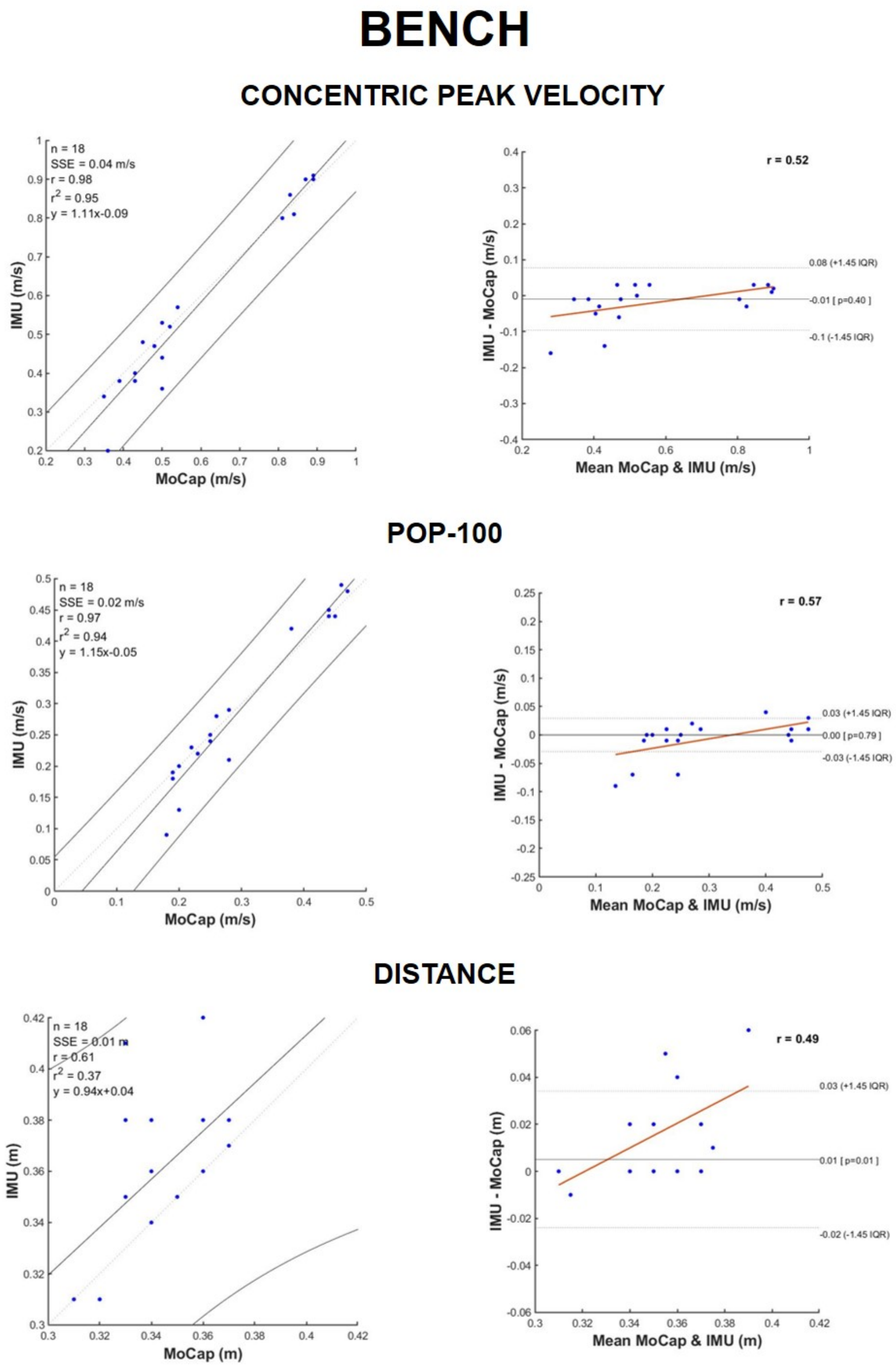

Figure 4. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all metrics recorded across all intensities for the bench press.

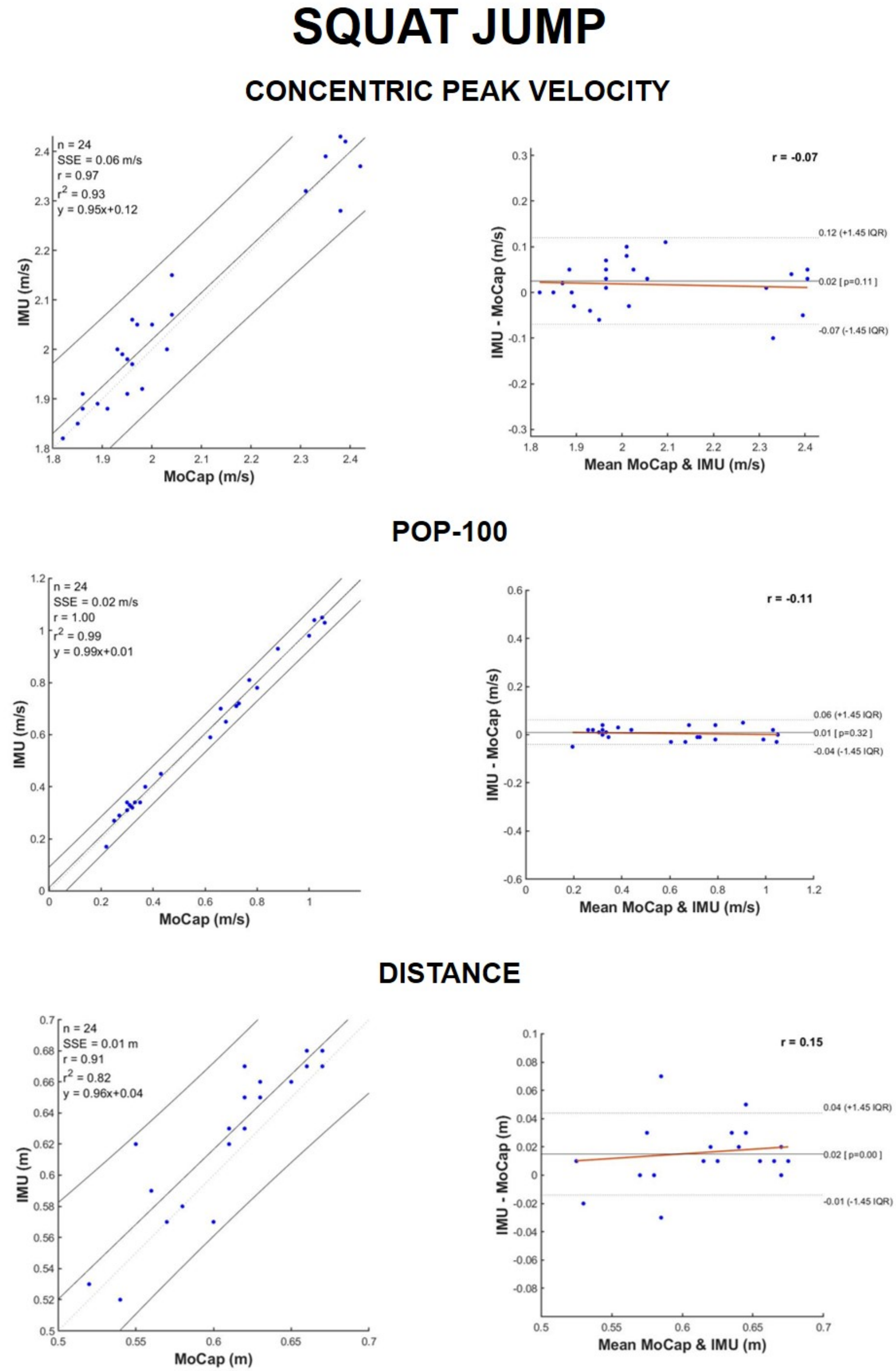

Figure 5. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all metrics recorded across all intensities for the squat jump.

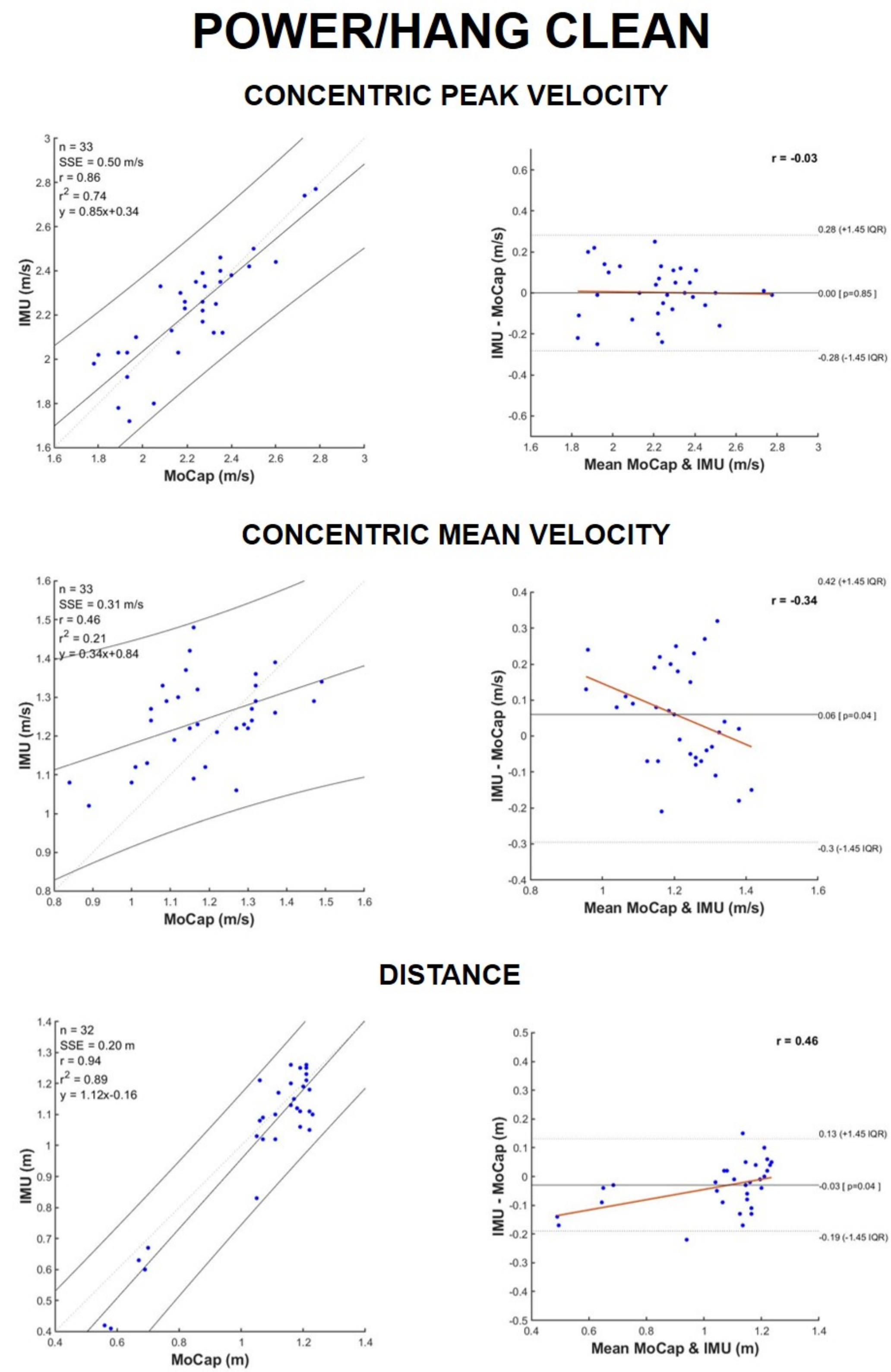

Figure 6. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all metrics recorded across all intensities for the power and hang clean.

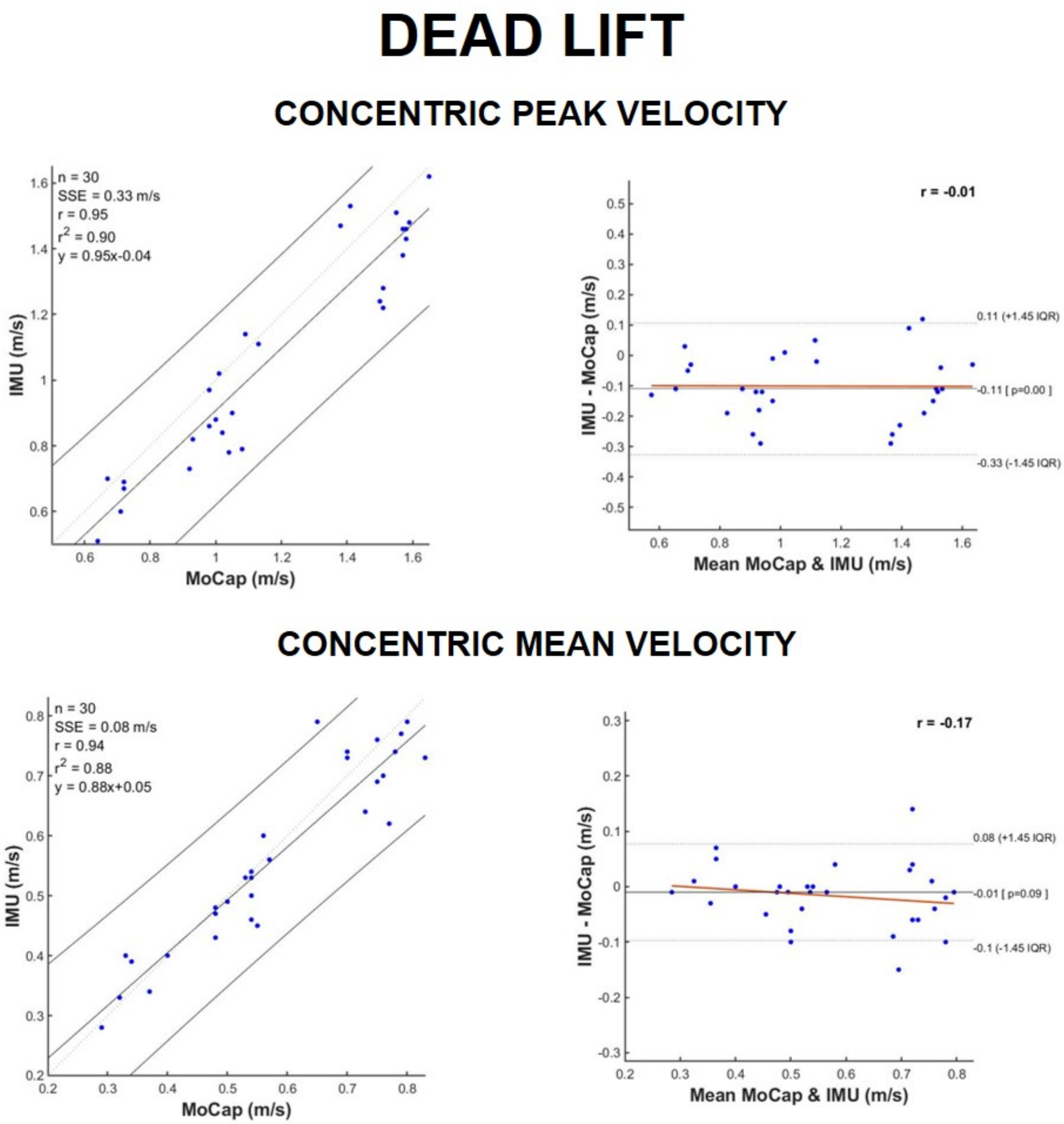

Figure 7. Results from the linear regression, Pearson correlation, and Bland-Altman analyses for all metrics recorded across all intensities for the deadlift