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Validity and Reliability of a Commercially Available Inertial Sensor for Measuring Barbell Mechanics during Weightlifting

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Abstract: This study aimed to assess the validity and reliability of a commercially available inertial measurement unit (Enode) for measuring barbell kinematics and kinetics during a snatch. In order to assess validity and within- and between-session reliability, thirteen competitive weightlifters conducted two snatches on two separate occasions at 85% of their one-repetition maximum. The Enode sensor was attached to the barbell, with each lift recorded via the device's native application concurrently with an 11-camera motion capture system. Passing–Bablok regression indicated fixed and proportional bias in some horizontal measures of barbell mechanics but showed no bias in all but one vertical variable. Collectively, this suggests that the Enode is a valid tool in the measurement of vertically derived, but not horizontally derived, variables from barbell kinematics. Within- and between-session reliability showed moderate to excellent ICCs, with trivial to small differences between repetitions and between sessions. However, between-session reliability showed lower levels of variability and, thus, may help coaches identify changes in technique over time (between sessions) with good accuracy. Overall the Enode offers a practical and affordable option for coaches seeking to monitor weightlifting technique in training environments.

Keywords: snatch; biomechanics; barbell; velocity

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1. Introduction

The monitoring of barbell mechanics is common in weightlifting to evaluate sport-specific performance. In this context, snatch barbell kinematics have been used to identify causes of success and failure [1–5], analyze differences in lifting technique between athletes with different performance levels [6–8] and weight categories [9], and to assess the weightlifters' physical abilities [10]. Based on the existing knowledge on barbell kinematics, this information may help coaches identify limiting factors during the lifts and, therefore, assist in the development of appropriate interventions.

Within the literature, kinematic measures of the barbell typically include its trajectory [11–14]: vertical position plotted against horizontal position. Previously, this information has been used to identify common barbell trajectory patterns exhibited by weightlifters [15], as well as their relationship to anthropometry [12] and the common patterns exhibited within weight categories and countries [13]. This information begins to highlight that even at the elite level, variations in trajectories exist and the success of a lift is multifaceted [1]. In addition to the barbell trajectory, barbell acceleration and velocity are often reported and have been shown to relate to key aspects of performance [16,17]. Furthermore, based on Newton's second law of motion, barbell kinetics (i.e., force and power) can be calculated from acceleration to provide information on the force application on the barbell [18,19].

The assessment of barbell mechanics is frequently realized using video analysis, with a large proportion of research using this as their primary method [1,11–14]. While this method of data capture is highly applicable it may require multiple cameras or specialist software, often reducing accessibility to coaches. It is for this reason, along with the enhancement of technology, that alternative devices (e.g., inertial measurement units [IMU]) have become increasingly popular. For application within weightlifting, the over-the-counter IMU-based Enode (formerly known as VmaxPro) (Blaumann & Meyer, Sports Technology UG, Magdeburg, Germany) is an easy-to-administer system to measure time series barbell kinematics instantaneously, providing clear, accessible information for the coach and lifter. Additionally, it is also able to synchronize the sensor data to a hand-held tablet, providing the user with simultaneous video feedback. The Enode system has previously been investigated for its validity in various strength-based exercises when assessing measures of average velocity, showing high levels of agreement with a three-dimensional (3D) motion capture (mean difference: −0.014 [95% CI −0.057–0.029], $r^2 = 0.99$) [20]. This is further supported by Fritschi, Seiler, and Gross [21], who found near perfect correlations between the Vmax Pro and 3D motion capture for mean and peak velocity, with a standard error of estimates between 2.4 and 6.8% ($r = 0.99$ [0.94–0.96] and 0.99 [0.92–0.99], respectively) across five different exercises, including both strength and ballistic type movements. While this provides some insight into the utility of the Enode to measure mean and peak velocity during general training exercises, its usefulness to analyze barbell mechanics in weightlifting has not yet been investigated. Therefore, the aim of this investigation is two-fold; (1) to assess the validity of the Enode relative to 3D motion capture criterion, and (2) to identify the within and between day reliability of various vertical and horizontal kinematic and kinetic barbell measures. It was hypothesized that the Enode would show good level of concurrent validity for barbell kinematic and kinetic data relative to the 3D motion capture system. Additionally, we also hypothesized that the Enode system would show acceptable within and between session reliability of barbell kinematic data.

2. Materials and Methods

2.1. Experimental Approach to the Problem

An observational cross-sectional design was used to identify the validity of the Enode's measurement of various kinematic and kinetic variables during the snatch. Secondly, these measures were then assessed for intra- and intersession reliability. A relative intensity of 85% snatch one-repetition maximum (1RM) was investigated, as this is a common intensity utilized during moderate–heavy sessions, or when over-reaching and tapering [22], thus making the findings of the results more ecologically valid to training for weightlifting performance.

2.2. Participants

Participants for this study were recruited from weightlifting clubs within the UK, consisting of trained and highly trained weightlifters as defined by McKay [23]. All participants were over the age of 18 and provided written consent prior to participation. Both male ($n = 7$) and female ($n = 6$) participants participated in this study ($N = 13$; snatch 1RM: 80 ± 18 kg; height: 168 ± 8.09 cm; mass: 74.57 ± 10.32 kg; and age: 30 ± 5.21 years). All participants met the criterion of being a competitive weightlifter at a level of no less than regional. All participants were free of injury prior to testing days and were free to withdraw at any point. Ethics approval was granted via an institutional ethics committee (protocol code 25296).

2.3. Procedures

All participants were required to visit the laboratory to perform the snatch on two separate occasions within the space of 2 to 7 days and with at least 48 h of recovery prior to testing. Participants were also asked to attend their laboratory sessions at the same time of day for each session to reduce any diurnal effects, along with the absence of caffeine. Upon arrival, the participants were given 10 min in which they could perform a self-selected warm up, reflective of their day-to-day training. Following this, a standardized warm up for the snatch was undertaken consisting of 1–2 sets of 2–5 repetitions of overhead squats, hang snatches, snatch pulls, and slow snatches with a 20 kg barbell for men and 15 kg barbell for women. No familiarization of exercises was required as all participants conducted the warm-up exercises regularly within their normal weightlifting training. Participants wore their normal training attire of weightlifting shoes and tight-fitting leggings or a singlet. Male participants lifted without a shirt, whilst women were required to wear a sports bra or weightlifting singlet. Participants were fitted with reflective markers on the right-hand side of the lower body. The relative intensity used in this investigation was based on the participants' most recent 1RM, which was conducted within 14 days of test day one in their own training environment using ascended loading. Participants performed 2 repetitions of loads starting at 70% and increasing to 85% in 5% increments. One-minute recovery was given between repetitions and 2–3 min between loads. If a lift was missed the participant was provided with a 2–3 min rest to attempt the weight again.

2.4. Data Capture and Processing

A total of 21 markers were attached to the participants right lower limbs and pelvis, specifically on the foot (metatarsals 1 and 5 and their heel), ankle (lateral and medial malleolus), shank (tibial cluster), knee (lateral and medial epicondyle), thigh (femoral cluster and left and right greater trochanter) and hip (left and right anterior superior iliac spine; left and right posterior superior iliac spine). An additional 2 markers were placed on either end of the barbell. All snatches were recorded using a motion capture system (criterion) (Qualysis Track Manager, QTM v2020.1 Göteborg, Sweden) with 11 infrared cameras in a controlled laboratory environment, capturing at a frequency of 200 hertz (Hz). Competition caliber barbells (15 kg for women and 20 kg for men) and weight plates were used during testing days (Eleiko, Halmstad, Sweden). The barbell was fitted with an Enode sensor (Enode Pro, Blaumann & Meyer, Sports Technology UG, Magdeburg, Germany) using a barbell sleeve provided by the manufacturer. The placement of the unit was between the right hand and the thigh when in the set position (Figure 1). This placement ensured the hip did not contact the device, as per company suggestion, whilst also keeping it as close to the barbell center as possible. Enode data were directly recorded in the device's native application (Enode Pro version 2.0.2, Blaumann & Meyer, Sports Technology UG, Magdeburg, Germany). The tri-axial acceleration was collected directly by the sensor at a sampling rate of 1000 Hz through a Bluetooth (65 Hz) connection with a tablet (iPad pro, Apple, Silicon Valley, CA, USA). Additionally, the application's synchronized video recording function was used to capture the lifts for visual inspection of the first pull at 60 frames per second. To ensure the knee joint was not obstructed by the weight plates, the iPad camera was placed on a tripod at an angle of 45 degrees to the front of the lifter, approximately 4 m away and 1 m from the ground.

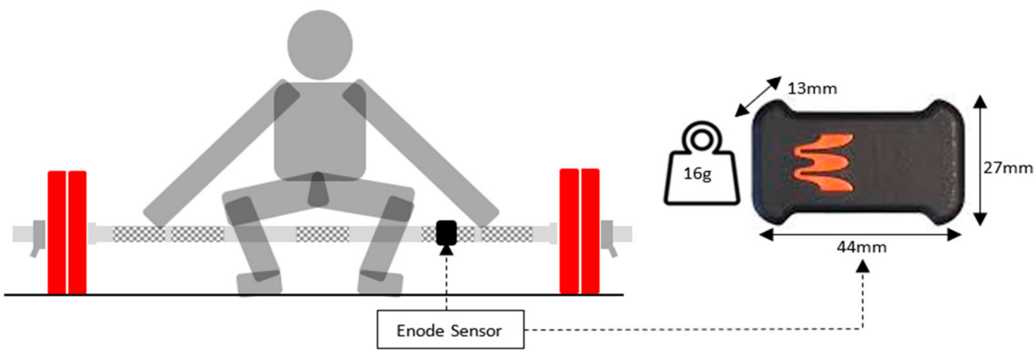

Figure 1. Enode placement relative to participant grip width during the set position.

Raw vertical (y) and horizontal (x) displacement data obtained from the reflective markers on the barbell were extracted from Qualysis into Visual 3D (Visual 3D x64, v2023.02.1, C-Motion, Boyds, MD, USA), where the knee angle was also calculated. This along with raw left and right barbell y and x displacement data were extracted for analysis in a custom MATLAB script (MATLAB version R2022b). The raw displacement data were filtered using a low-pass, fourth-order Butterworth filter with a cut-off frequency of 4 Hz, as determined by residual analysis of 30 randomly selected samples of both left and right vertical barbell displacement. The filtered barbell displacement data were then differentiated twice to obtain the vertical velocity and vertical acceleration.

In the next step, the lifting phases of the snatch were identified from the Enode and the motion capture system data as follows: 1st pull (lift off to first peak knee extension), transition (first peak knee extension to first peak positive barbell horizontal displacement), 2nd pull (first peak positive barbell horizontal displacement to peak positive vertical barbell velocity), turnover (peak positive vertical barbell velocity to peak negative barbell velocity), and catch (peak negative barbell velocity to deep squat position). It should be noted that the end of the first pull was determined using the first peak knee angle value identified within the MATLAB script; however, as this is not possible using the Enode, the end of the first pull was instead identified when the knee visibly reached its first peak extension, one frame prior to the knee re-bending [24]. This subjective method of identification has previously been reported [25]. As per communications with the company, the acceleration measured from the Enode was integrated with respect to time and a threshold of 0.005 m/s was used to identify the start and end of the snatch movement. Once this threshold was reached, displacement was calculated. This threshold was matched within the motion capture analysis script to allow for comparison. Figures 2 and 3 display the variables that were extracted and analyzed.

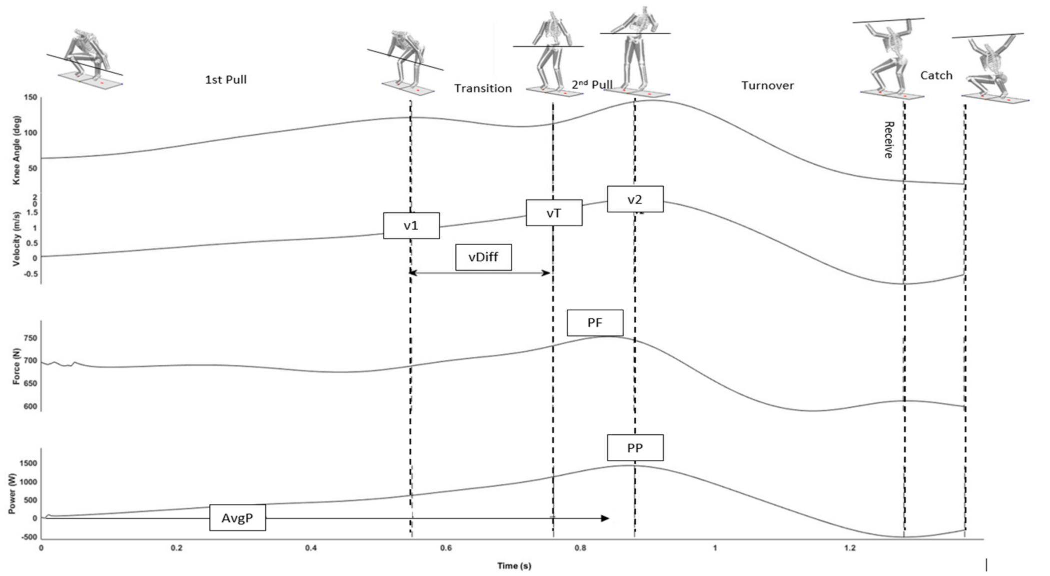

Figure 2. Kinematic and kinetic time series displaying discreet variable extrapolations, where v = velocity, 1 = first pull, T = transition, Diff = difference, 2 = second pull, PF = peak force, PP = peak power, and AvgP = average power. The arrows distinguish the phase(s) from which the data were extrapolated.

The calculation for barbell vertical force and power in the Enode application is as follows, as stated by the company:

$$\text{Peak Power} = (\text{vertical acceleration} + 1) \times \text{gravity} \times \text{vertical velocity} \times \text{mass}, \quad (1)$$

$$\text{Mean Power} = \text{vertical velocity} \times (9.81 + \text{vertical velocity}/\text{time}) \times \text{mass}, \quad (2)$$

$$\text{Force} = (\text{vertical acceleration} + 1) \times \text{gravity} \times \text{mass}. \quad (3)$$

The script utilized within our methods calculated barbell vertical force and power using the methods adopted from Garhammer [26], where work was calculated as the sum of kinetic and potential energy.

$$\text{Force} = \text{vertical work/vertical displacement} \quad (4)$$

$$\text{Power} = \text{vertical force} \times \text{vertical velocity} \quad (5)$$

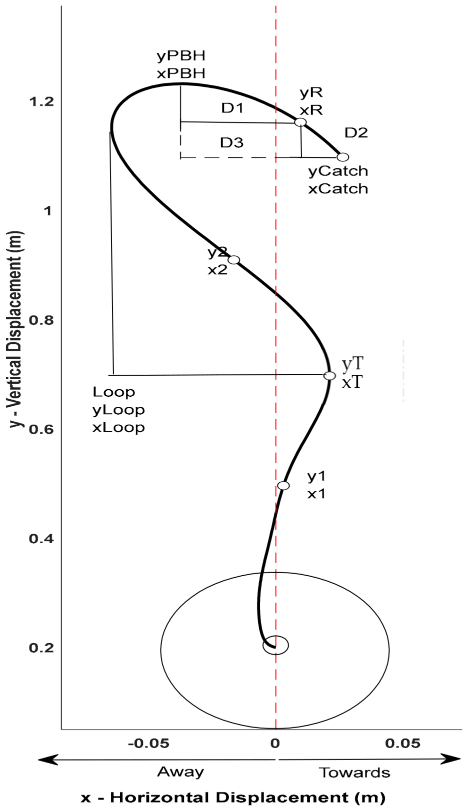

Figure 3. Barbell trajectory with identified coordinates extracted for analysis, where x refers to horizontal and y to vertical. 1 = first pull, T = transition, 2 = second pull, PBH = peak barbell height, R = receive, D1 = vertical drop distance between PBH and receive, D2 = vertical drop distance between receive and catch, and D3 = vertical drop distance between PBH and catch. The red line displays a vertical intercept from the start of the lift with "away" and "towards" identifying direction of the barbell trajectory relative to the athlete.

2.5. Statistical Analysis

2.5.1. Validity

Relative (compared-to-criterion) validity was assessed using Lin's concordance correlation coefficient (CCC) with 95% CI [27] using the average of session 1 and session 2 from each device. The strength-of-agreement criteria for CCC were categorized as poor (CCC < 0.9), moderate (CCC < 0.95), substantial (CCC < 0.99), and almost perfect (CCC $\geq$ 0.99) [28].

Absolute levels of validity to assess for fixed and proportional bias were obtained using Passing–Bablok regression (MedCalc, v20.2017). This has previously been identified as an appropriate test to compare methods because it enables measurement error in both the x (Enode) and y (criterion) variables [29]. Interpretations of fixed and proportional bias (difference) were determined as follows: If the 95% CI of the intercept contained the value 0, then there was no fixed bias between devices (i.e., no fixed difference between variable A's measurement between the Enode and criterion). If the 95% CI of the slope contained 1, then there was no proportional difference, so no difference (proportional bias) existed between devices (i.e., as variable A's measurement value from the criterion increases, the difference between the measurements obtained by the Enode and criterion remains constant) [30]. In the instance where significant fixed and/or proportional bias was present, regression equations will be presented to allow for measurement correction. The residual standard deviation (RSD) is also presented to provide the absolute measure of error and is also expressed as a percentage of the Enode's mean.

2.5.2. Reliability

Within and between session reliability of the Enode was assessed using the standard error of measurement (SEM) and Interclass Correlation Coefficient (ICC; two-way random with absolute agreement), where the ICC was determined using MedCalc with SEM calculated in a custom spreadsheet. The ICCs were rated based on the guidelines suggested by Koo and Li [31] using the 95% CI boundary, where descriptors of 'poor' (<0.5), 'moderate' (0.5–0.75), 'good' (0.75–0.9), and 'excellent' (>0.9) were used. Once relative reliability was established, SEM was determined to assess absolute interunit reliability from the mean of each variable, where SEM was calculated as the product of the SD of the pooled mean values and the square root of 1 minus the ICC [32].

$$\mathrm{SEM} = \mathrm{SD}^{\mathrm{pooled}} \times \sqrt{1 - ICC} \tag{6}$$

Using the SEM, the smallest detectable difference (SDD) was calculated as

$$\mathrm{SDD} = \left(1.96 \times \sqrt{2}\right) \times \mathrm{SEM}. \tag{7}$$

In practice, if the difference between two units ± SDD is identified, this would indicate that a meaningful change outside of the error of the test–retest has occurred [33]. Hedges' g effect sizes were also calculated using a custom spreadsheet to analyze both within and between session differences of both the Enode and criterion. The effect size values and descriptors were interpreted using the conventions outlined by Cohen [34]: 'trivial' (<0.20), 'small' (0.21–0.50), 'moderate' (0.51–0.80), and 'large' (>0.80).

3. Results

3.1. Validity

Table 1 displays the relative and absolute validity of the Enode. Passing–Bablok regression indicated fixed (yT, x2, xPBH, and xLoop) and proportional bias (xT, xR, xCatch, and PF) was present in some of the variables. A correction for the differences between the Enode and criterion can be applied using the regression formula, using the intercept and slope provided in Table 1 (8), where X stands for the specific parameter (e.g., yT):

$$\text{Enode(X)\_corrected} = \text{Intercept(X)} + \text{Enode(X)} \times \text{Slope(X)}. \tag{8}$$

All other variables displayed no fixed or proportional bias. Relative reliability displayed 95% confidence ranges from poor to near perfect (Figure 4). The residual standard deviation percentage displayed the greatest measurement errors within horizontal displacement variables. Collectively, this suggests that the Enode is a valid tool in the measurement of some, but not all, biomechanical measures of the barbell during the snatch.

Table 1. Between-unit comparison of the Enode and criterion using the average of session 1 and 2.

Phase	Variable	Enode Mean ± SD [95% CI]	3D Criterion Mean ± SD [95% CI]	Intercept [95% CI]	Slope [95% CI]	RSD [95% CI]	RSD (%)
1st pull	v1	1.06 ± 0.18 [0.61–1.52]	1.15 ± 0.2 [0.66–1.65]	−0.01 [−0.2–0.17]	1.1 [0.94–1.29]	0.04 [−0.08–0.08]	4%
	x1	1.94 ± 1.65 [1.11–2.76]	1.04 ± 1.52 [0.6–1.49]	−0.45 [−1.98–0.06]	0.94 [0.64–1.73]	0.88 [−1.73–1.73]	45%
	y1	25.96 ± 4.27 [14.86–37.06]	30.95 ± 4.44 [17.72–44.18]	1.01 [−38.03–14.61]	1.17 [0.61–2.71]	2.48 [−4.86–4.86]	10%
Transition	vT	1.51 ± 0.16 [0.86–2.15]	1.51 ± 0.13 [0.87–2.16]	0.23 [0–0.51]	0.86 [0.67–1]	0.03 [−0.05–0.05]	2%
	xT	**5.3 ± 3.24 [3.04–7.57]**	**3.68 ± 2.18 [2.11–5.26]**	**0.75 [−1.67–1.6]**	**0.63 [0.3–0.99]**	**1.22 [−2.40–2.40]**	**23%**
	yT	***50.33 ± 6.51 [28.81–71.85]***	***51.03 ± 5.59 [29.21–72.84]***	***12.7 [0.68–22.63]***	***0.77 [0.58–1]***	***1.61 [−3.15–3.15]***	***3%***
	vLoss	0.44 ± 0.18 [0.25–0.63]	0.36 ± 0.15 [0.21–0.51]	−0.07 [−0.21–0.10]	0.93 [0.55–1.31]	0.07 [−0.14–0.14]	47%

Table 1. *Cont.*

Phase	Variable	Enode Mean ± SD [95% CI]	3D Criterion Mean ± SD [95% CI]	Intercept [95% CI]	Slope [95% CI]	RSD [95% CI]	RSD (%)
2nd Pull	v2	2.08 ± 0.16 [1.19–2.97]	2 ± 0.15 [1.15–2.86]	0.07 [−0.35–0.31]	0.93 [0.81–1.12]	0.02 [−0.05–0.05]	1%
	x2	***−0.63 ± 4.85 [−0.36– -0.89]***	***−1.81 ± 3.28 [−1.04–2.58]***	***−0.75 [−1.61–1.01]***	***0.67 [0.38–1.22]***	***1.87 [−3.67–3.67]***	***300%***
	y2	81.11 ± 6.33 [46.43–115.79]	79.65 ± 6.24 [45.6–113.71]	1.35 [−15.78–14.23]	0.97 [0.8–1.17]	1.16 [−2.27–2.27]	1%
Turnover	***xPBH***	***3.11 ± 5.53 [1.78–4.44]***	***−0.45 ± 3.68 [−0.26–0.64]***	***−1.96 [−3.66–1.19]***	***0.67 [0.39–1.06]***	***2.53 [−4.97–4.97]***	***81%***
	yPBH	118.62 ± 9.56 [67.91–169.34]	116.42 ± 8.99 [66.65–166.19]	4.88 [−13.71–24.4]	0.94 [0.78–1.09]	1.52 [−2.97–2.97]	1%
Receive	**xR**	**9.07 ± 6.85 [5.19–12.95]**	**3.83 ± 4.22 [2.19–5.47]**	**−0.64 [−3.5–2.03]**	**0.55 [0.28–0.89]**	**2.93 [−5.74–5.74]**	**32%**
	yR	108.66 ± 8.5 [62.2–155.11]	107.75 ± 8.35 [61.69–153.82]	0.88 [−24.82–21.61]	0.99 [0.79–1.23]	1.67 [−3.27–3.27]	2%
Catch	D1	9.96 ± 4.16 [5.7–14.22]	8.66 ± 3.53 [4.96–12.37]	0.22 [−1.85–1.33]	0.83 [0.73–1.09]	0.69 [−1.34–1.34]	7%
	xCatch	**12.2 ± 8.05 [6.98–17.41]**	**5.37 ± 4.26 [3.08–7.67]**	**0.55 [−3.64–3.91]**	**0.43 [0.14–0.8]**	**3.34 [−6.55–6.55]**	**27%**
	yCatch	94.87 ± 8.06 [54.31–135.42]	95.6 ± 8.26 [54.73–136.48]	−6.7 [−88.35–25.04]	1.08 [0.74–1.97]	2.14 [−4.2–4.2]	2%
	D2	13.79 ± 6.05 [7.9–19.69]	12.15 ± 6.15 [6.96–17.35]	−1.93 [−3.57–1.98]	1 [0.78–1.15]	0.99 [−1.94–1.94]	7%
	D3	23.76 ± 9.36 [13.6–33.91]	20.81 ± 8.97 [11.92–29.71]	−1.62 [−5.58–0.8]	0.94 [0.83–1.16]	1.46 [−2.87–2.87]	6%
	xLoop	***−3.26 ± 5.19 [−1.87–4.66]***	***−5.01 ± 3.44 [−2.87–7.15]***	***−2.79 [−4.48–1.18]***	***0.67 [0.32–1.09]***	***2.12 [−4.16–4.16]***	***65%***
	yLoop	101.23 ± 7.96 [57.95–144.5]	101.78 ± 6.98 [58.27–145.3]	19.83 [−29.72–41.07]	0.82 [0.61–1.3]	2.75 [−5.39–5.39]	3%
	Loop	8.67 ± 2.54 [4.96–12.37]	8.69 ± 1.81 [4.98–12.41]	2.47 [−4.78–5.92]	0.72 [0.35–1.61]	1.2 [−2.36–2.36]	14%
Force and Power	AvgP	770 ± 176 [441–1099]	745 ± 176 [427–1064]	−10 [−153.97–63.22]	0.97 [0.86–1.2]	31 [−61–61]	4%
	PP	1799 ± 473 [1030–2569]	1636 ± 372 [937–2336]	157.13 [−147.02–434.16]	0.82 [0.67–1.04]	85 [−166–166]	5%
	PF	**1005 ± 238 [576–1435]**	**838 ± 177 [480–1197]**	**102.32 [−62.44–200.07]**	**0.73 [0.61–0.93]**	**50 [−99–99]**	**5%**

SD = standard deviation, CI = confidence interval, and RSD = residual standard deviation. **Bold** values represent fixed bias and **bold italics** represent proportional bias.

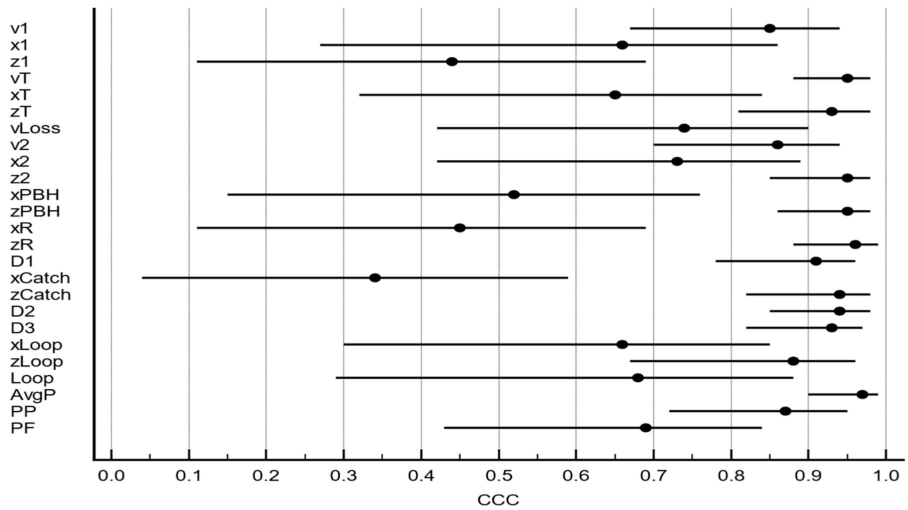

Figure 4. Strength of agreement between Enode and 3D criterion using concordance correlation coefficient (CCC).

3.2. Reliability

Within-session relative reliability showed ICCs ranging from poor to excellent, with trivial to small differences between repetitions for both session 1 (Table 2) and session 2 (Table 3). Between-session reliability showed good to excellent ICCs, with the exception of xCatch, which displayed a moderate ICC value of 0.689 [0.048, 0909], with mainly trivial differences displayed between sessions (Table 4). Overall, between-session reliability was shown to be greater than that of within-session reliability.

Table 2. Mean and standard deviation for all variables for the Enode, with within-session reliability statistics and Hedges' g effect size data with 95% confidence intervals.

		Session 1					
Phase	**Variable**	**Rep 1 Mean ± SD [95% CI]**	**Rep 2 Mean ± SD [95% CI]**	**ICC**	**SEM**	**SDD**	**Hedges *g***
1st pull	v1	1.08 ± 0.18 [0.62, 1.54]	1.04 ± 0.20 [0.59, 1.48]	0.940 [0.757, 0.983]	0.00	0.01	0.2 [−0.61, 1.02]
	x1	2.25 ± 2.13 [1.29, 3.21]	1.95 ± 1.76 [1.12, 2.79]	0.667 [0.208, 0.885]	0.08	0.23	0.14 [−0.67, 0.96]
	y1	26.43 ± 5.32 [15.13, 37.73]	26.18 ± 5.00 [14.99, 37.37]	0.871 [0.629, 0.959]	0.05	0.13	0.05 [−0.76, 0.86]
Transition	vT	1.52 ± 0.15 [0.87, 2.16]	1.52 ± 0.20 [0.87, 2.17]	0.727 [0.306, 0.909]	0.00	0.01	−0.04 [−0.85, 0.77]
	xT	5.53 ± 3.75 [3.17, 7.90]	5.52 ± 3.48 [3.16, 7.87]	0.837 [0.544, 0.948]	0.00	0.01	0.00 [−0.81, 0.81]
	yT	50.23 ± 6.62 [28.76, 71.71]	50.97 ± 7.05 [29.18, 72.76]	0.772 [0.407, 0.924]	0.18	0.49	−0.10 [−0.91, 0.71]
	vLoss	0.44 ± 0.20 [0.25, 0.62]	0.48 ± 0.23 [0.28, 0.69]	0.848 [0.587, 0.951]	0.01	0.03	−0.21 [−1.03, 0.60]

Table 2. *Cont.*

		Session 1					
Phase	**Variable**	**Rep 1 Mean ± SD [95% CI]**	**Rep 2 Mean ± SD [95% CI]**	**ICC**	**SEM**	**SDD**	**Hedges *g***
2nd Pull	v2	2.08 ± 0.16 [1.19, 2.97]	2.09 ± 0.17 [1.20, 2.98]	0.928 [0.783, 0.977]	0.00	0.00	−0.05 [−0.85, 0.76]
	x2	−0.14 ± 5.11 [−0.08, −0.20]	−0.09 ± 5.27 [−0.05, −0.13]	0.901 [0.705, 0.969]	0.01	0.02	−0.01 [−0.82, 0.80]
	y2	80.85 ± 7.21 [46.29, 115.42]	81.88 ± 6.34 [46.87, 116.88]	0.705 [0.280, 0.900]	0.28	0.77	−0.15 [−0.96, 0.66]
Turnover	xPBH	3.44 ± 5.98 [1.97, 4.91]	4.02 ± 6.98 [2.30, 5.73]	0.756 [0.371, 0.919]	0.14	0.39	−0.09 [−0.90, 0.72]
	yPBH	117.90 ± 10.18 [67.49, 168.31]	118.28 ± 9.79 [67.71, 168.84]	0.766 [0.386, 0.923]	0.09	0.25	−0.04 [−0.85, 0.77]
Receive	xR	9.42 ± 7.90 [5.39, 13.44]	9.74 ± 8.80 [5.57, 13.90]	0.629 [0.124, 0.871]	0.10	0.27	−0.04 [−0.85, 0.77]
	yR	108.09 ± 8.96 [61.88, 154.31]	106.79 ± 9.90 [61.14, 152.45]	0.728 [0.322, 0.908]	0.34	0.94	0.13 [−0.68, 0.94]
Catch	D1	9.81 ± 5.02 [5.61, 14.00]	11.48 ± 5.71 [6.57, 16.39]	0.841 [0.518, 0.950]	0.33	0.93	−0.3 [−1.12, 0.51]
	xCatch	12.62 ± 9.01 [7.23, 18.02]	12.19 ± 12.10 [6.98, 17.40]	0.519 [0.048, 0.827]	0.15	0.41	0.04 [−0.77, 0.85]
	yCatch	95.75 ± 8.96 [54.81, 136.68]	93.85 ± 10.58 [53.73, 133.98]	0.696 [0.271, 0.895]	0.52	1.45	0.19 [−0.62, 1.00]
	D2	12.35 ± 5.00 [7.07, 17.62]	12.94 ± 4.99 [7.41, 18.47]	0.877 [0.654, 0.960]	0.10	0.29	−0.11 [−0.93, 0.70]
	D3	22.15 ± 8.96 [12.68, 31.63]	24.42 ± 9.57 [13.98, 34.86]	0.925 [0.682, 0.979]	0.31	0.86	−0.24 [−1.05, 0.58]
	xLoop	−2.68 ± 5.31 [−1.53, −3.82]	−2.03 ± 6.73 [−1.16, −2.90]	0.822 [0.518, 0.942]	0.14	0.38	−0.10 [−0.91, 0.71]
	yLoop	101.25 ± 8.48 [57.96, 144.53]	100.42 ± 8.69 [57.49, 143.36]	0.584 [0.057, 0.853]	0.27	0.74	0.09 [−0.72, 0.90]
	Loop	8.21 ± 2.64 [4.70, 11.72]	7.95 ± 3.47 [4.55, 11.35]	0.850 [0.583, 0.952]	0.05	0.14	0.08 [−0.73, 0.89]
Force and Power	AvgP	760 ± 177 [435, 1086]	760 ± 175 [435, 1085]	0.990 [0.968, 0.997]	0.01	0.02	0.00 [−0.81, 0.81]
	PP	1781 ± 482 [1019, 2542]	1802 ± 511 [1032, 2572]	0.964 [0.889, 0.989]	2.03	5.63	−0.04 [−0.85, 0.77]
	PF	1000 ± 236 [572, 1427]	1004 ± 248 [575, 1433]	0.985 [0.950, 0.995]	0.25	0.69	−0.02 [−0.83, 0.79]

Table 3. Session 2 mean and standard deviation for all variables for the Enode, with within-session reliability statistics and Hedges' *g* effect size data with 95% confidence intervals.

		Session 2					
Phase	**Variable**	**Rep 1 Mean ± SD [95% CI]**	**Rep 2 Mean ± SD [95% CI]**	**ICC**	**SEM**	**SDD**	**Hedges *g***
1st pull	v1	1.06 ± 0.17 [0.61–1.52]	1.08 ± 0.2 [0.62–1.54]	0.835 [0.543, 0.947]	0.00	0.01	−0.1 [−0.91, 0.71]
	x1	1.98 ± 2.06 [1.13–2.82]	1.57 ± 2.01 [0.9–2.24]	0.829 [0.546, 0.944]	0.08	0.23	0.2 [−0.62, 1.01]
	y1	25.57 ± 4.19 [14.64–36.5]	25.65 ± 4.52 [14.69–36.62]	0.707 [0.266, 0.901]	0.02	0.06	−0.02 [−0.83, 0.79]
Transition	vT	1.49 ± 0.19 [0.85–2.12]	1.5 ± 0.19 [0.86–2.14]	0.738 [0.329, 0.913]	0.00	0.01	−0.05 [−0.86, 0.76]
	xT	5.52 ± 3.31 [3.16–7.88]	4.65 ± 3.52 [2.66–6.63]	0.836 [0.551, 0.947]	0.18	0.49	0.25 [−0.57, 1.06]
	yT	50.12 ± 7.01 [28.69–71.54]	50 ± 7.28 [28.62–71.37]	0.833 [0.534, 0.946]	0.02	0.07	0.02 [−0.79, 0.83]
	vLoss	0.42 ± 0.19 [0.24–0.6]	0.42 ± 0.15 [0.24–0.6]	0.869 [0.624, 0.958]	0.00	0.00	0.00 [−0.81, 0.81]
2nd Pull	v2	2.07 ± 0.18 [1.18–2.95]	2.09 ± 0.17 [1.2–2.99]	0.950 [0.841, 0.984]	0.00	0.01	−0.11 [−0.92, 0.70]
	x2	−0.38 ± 4.89 [−0.22–0.54]	−1.89 ± 5.34 [−1.08–2.7]	0.831 [0.520, 0.946]	0.31	0.86	0.29 [−0.53, 1.10]
	y2	81.05 ± 6.4 [46.4–115.71]	80.66 ± 7.62 [46.18–115.15]	0.861 [0.606, 0.956]	0.07	0.20	0.05 [−0.76, 0.86]
Turnover	xPBH	3.5 ± 6.46 [2–5]	1.5 ± 6.44 [0.86–2.14]	0.649 [0.206, 0.876]	0.59	1.64	0.30 [−0.51, 1.11]
	yPBH	118.42 ± 10.71 [67.79–169.05]	119.88 ± 10.72 [68.63–171.14]	0.893 [0.696, 0.966]	0.24	0.66	−0.13 [−0.94, 0.68]
Receive	xR	9.42 ± 8.2 [5.39–13.45]	7.7 ± 8.3 [4.41–10.99]	0.630 [0.156, 0.870]	0.52	1.45	0.20 [−0.61, 1.01]
	yR	108.84 ± 10.95 [62.31–155.37]	110.91 ± 10.21 [63.49–158.32]	0.760 [0.398, 0.919]	0.51	1.41	−0.19 [−1.00, 0.62]
Catch	D1	9.58 ± 5.34 [5.49–13.68]	8.98 ± 2.71 [5.14–12.81]	0.504 [0.057, 0.819]	0.21	0.59	0.14 [−0.67, 0.95]
	xCatch	13.02 ± 10.04 [7.46–18.59]	10.95 ± 10.61 [6.27–15.63]	0.613 [0.125, 0.863]	0.64	1.78	0.19 [−0.62, 1.01]
	yCatch	93.81 ± 7.86 [53.7–133.91]	96.05 ± 9.96 [54.99–137.12]	0.798 [0.477, 0.933]	0.50	1.40	−0.24 [−1.05, 0.57]
	D2	15.03 ± 8.67 [8.6–21.46]	14.85 ± 6.64 [8.5–21.2]	0.870 [0.625, 0.959]	0.03	0.09	0.02 [−0.79, 0.83]
	D3	24.62 ± 10.8 [14.09–35.14]	23.83 ± 9.05 [13.64–34.02]	0.962 [0.884, 0.988]	0.08	0.21	0.08 [−0.73, 0.89]
	xLoop	−3.22 ± 5.29 [−1.85–4.6]	−5.12 ± 5.76 [−2.93–7.3]	0.754 [0.374, 0.918]	0.47	1.31	0.33 [−0.48, 1.15]
	yLoop	100.89 ± 8.43 [57.76–144.03]	102.34 ± 10.48 [58.59–146.09]	0.835 [0.558, 0.946]	0.29	0.82	−0.15 [−0.96, 0.66]
	Loop	8.75 ± 2.59 [5.01–12.49]	9.76 ± 2.88 [5.59–13.93]	0.702 [0.287, 0.898]	0.28	0.76	−0.36 [−1.17, 0.46]
Force and Power	AvgP	772 ± 183 [442 −1102]	785 ± 176 [450 −1121]	0.975 [0.924, 0.992]	1.03	2.85	−0.07 [−0.88, 0.74]
	PP	1800 ± 476 [1031–2570]	1814 ± 443 [1039–2590]	0.968 [0.898, 0.990]	1.25	3.47	−0.03 [−0.84, 0.78]
	PF	1014 ± 244 [580–1447]	1004 ± 234 [575–1433]	0.968 [0.902, 0.990]	0.89	2.48	0.04 [−0.77, 0.85]

Table 4. Between-session mean and standard deviation for all variables for the Enode, with between-session reliability statistics and Hedges' g effect size data with 95% confidence intervals.

Phase	Variable	Session 1 Mean ± SD [95% CI]	Session 2 Mean ± SD [95% CI]	ICC	SEM	SDD	Hedges g
1st pull	v1	1.06 ± 0.19 [0.61–1.51]	1.07 ± 0.18 [0.61–1.53]	0.917 [0.727, 0.975]	0.00	0.00	−0.05 [−0.86, 0.76]
	x1	2.1 ± 1.78 [1.2–3]	1.77 ± 1.95 [1.02–2.53]	0.732 [0.115, 0.918]	0.09	0.24	0.17 [−0.64, 0.98]
	y1	26.3 ± 4.98 [15.06–37.55]	25.61 ± 4.01 [14.66–36.56]	0.881 [0.620, 0.963]	0.12	0.33	0.15 [−0.66, 0.96]
Transition	vT	1.52 ± 0.16 [0.87–2.17]	1.49 ± 0.18 [0.85–2.13]	0.942 [0.816, 0.982]	0.00	0.01	0.17 [−0.64, 0.98]
	xT	5.52 ± 3.45 [3.16–7.88]	5.08 ± 3.29 [2.91–7.26]	0.919 [0.741, 0.975]	0.06	0.17	0.13 [−0.68, 0.94]
	yT	50.6 ± 6.42 [28.97–72.23]	50.06 ± 6.82 [28.66–71.46]	0.966 [0.890, 0.989]	0.05	0.14	0.08 [−0.73, 0.89]
	vLoss	0.46 ± 0.21 [0.26–0.66]	0.42 ± 0.17 [0.24–0.6]	0.862 [0.565, 0.957]	0.01	0.02	0.20 [−0.61, 1.01]
2nd Pull	v2	2.09 ± 0.16 [1.19–2.98]	2.08 ± 0.17 [1.19–2.97]	0.954 [0.850, 0.986]	0.00	0.00	0.06 [−0.75, 0.87]
	x2	−0.12 ± 5.05 [−0.07–0.16]	−1.13 ± 4.93 [−0.65–1.62]	0.937 [0.797, 0.981]	0.13	0.35	0.20 [−0.62, 1.01]
	y2	81.37 ± 6.25 [46.58–116.15]	80.86 ± 6.77 [46.29–115.43]	0.943 [0.817, 0.983]	0.06	0.17	0.08 [−0.73, 0.89]
Turnover	xPBH	3.73 ± 6.07 [2.13–5.32]	2.5 ± 5.88 [1.43–3.57]	0.834 [0.474, 0.949]	0.25	0.69	0.20 [−0.61, 1.01]
	yPBH	118.09 ± 9.35 [67.6–168.58]	119.15 ± 10.42 [68.21–170.1]	0.930 [0.777, 0.979]	0.14	0.39	−0.10 [−0.91, 0.71]
Receive	xR	9.58 ± 7.5 [5.48–13.67]	8.56 ± 7.44 [4.9–12.22]	0.818 [0.403, 0.945]	0.22	0.60	0.13 [−0.68, 0.94]
	yR	107.44 ± 8.75 [61.51–153.38]	109.87 ± 9.93 [62.9–156.85]	0.785 [0.324, 0.933]	0.56	1.56	−0.25 [−1.06, 0.56]
Catch	D1	10.65 ± 5.2 [6.09–15.2]	9.28 ± 3.65 [5.31–13.25]	0.825 [0.456, 0.946]	0.29	0.80	0.30 [−0.52, 1.11]
	xCatch	12.41 ± 9.23 [7.1–17.71]	11.98 ± 9.25 [6.86–17.11]	0.698 [0.048, 0.909]	0.12	0.33	0.05 [−0.76, 0.85]
	yCatch	94.8 ± 9.02 [54.27–135.33]	94.93 ± 8.53 [54.34–135.52]	0.826 [0.412, 0.948]	0.03	0.08	−0.01 [−0.82, 0.80]
	D2	12.64 ± 4.84 [7.24–18.05]	14.94 ± 7.45 [8.55–21.33]	0.897 [0.599, 0.970]	0.37	1.02	−0.35 [−1.17, 0.46]
	D3	23.29 ± 9.15 [13.33–33.25]	24.22 ± 9.87 [13.87–34.58]	0.966 [0.894, 0.99]	0.09	0.24	−0.09 [−0.9, 0.72]
	xLoop	−2.35 ± 5.77 [−1.35–3.36]	−4.17 ± 5.22 [−2.39–5.95]	0.862 [0.555, 0.958]	0.34	0.94	0.32 [−0.49, 1.14]
	yLoop	100.83 ± 7.6 [57.72–143.94]	101.62 ± 9.11 [58.17–145.06]	0.894 [0.655, 0.968]	0.13	0.36	−0.09 [−0.90, 0.72]
	Loop	8.08 ± 2.96 [4.62–11.53]	9.25 ± 2.55 [5.3–13.21]	0.787 [0.332, 0.934]	0.27	0.75	−0.41 [−1.23, 0.41]
Force and Power	AvgP	760 ± 176 [435–1086]	779 ± 178 [446–1112]	0.986 [0.952, 0.996]	1.10	3.05	−0.10 [−0.91, 0.71]
	PP	1791 ± 492 [1025–2557]	1807 ± 456 [1035–2580]	0.993 [0.978, 0.998]	0.66	1.84	−0.03 [−0.84, 0.78]
	PF	1002 ± 241 [574–1430]	1009 ± 237 [578–1440]	0.997 [0.989, 0.999]	0.20	0.57	−0.03 [−0.84, 0.78]

4. Discussion

The primary aim of this investigation was to assess the validity and reliability of a commercially available IMU (Enode) to measure barbell kinematics and kinetics during a snatch. The results show that the Enode is valid and reliable for most variables, but it often overestimated horizontal-displacement-related data. These findings are important because, to the authors' knowledge, this is the first study to establish the validity and reliability of the Enode for snatches and associated variables that have previously been identified as measures of technique. Furthermore, our findings indicate that the Enode may be an affordable and accessible option to help coaches monitor weightlifting technique during a snatch, particularly between sessions, providing an accessible method that does not rely on laboratory or bespoke motion capture systems.

While this may be the first study to investigate the validity and reliability of the Enode within the context of weightlifting, it has previously been studied for its validity and reliability across various lower-body ballistic and non-ballistic movements, such as squatting [10,21,35–37], jumping [21,38,39], and the hang power snatch [21]. The two primary variables extracted for comparison against 3D motion capture criterion were the mean and peak velocity. In the present study, peak velocity (and instantaneous end-of-phase velocity; v1, vT, and v2) was extracted for analysis given it is important within weightlifting-type exercises, as it provides an indication as to whether the barbell will be displaced at a high enough point for the athlete to receive it. Only one study to date has attempted to assess the validity and reliability of the Enode during a weightlifting derivative [21]. This study showed that Enode peak velocity demonstrated proportional bias, but these data had been pooled across different ballistic and non-ballistic exercises and so should be interpreted with caution [21]. Additionally, the aforementioned authors only used a 20 kg barbell for the hang power snatch, which may likely incur a longer active deceleration following the second pull, which may account for the systematic underestimation of mean velocity across all devices.

A potential consideration around unit validity vs. criterion is the placement of the unit with respect to the barbell. Ideally, a marker would be placed directly on the unit; however, pilot data from the authors detected inaccuracies in horizontal and vertical displacement of the marker due to the rotation of the barbell. As displacement measures were also assessed for validity and reliability, it was deemed appropriate to compare the Enode to the calculated barbell center of mass (CoM), taken as the average of the two barbell end markers. The present study placed the Enode between the grip of the athlete and their thigh during the set position, as close to the center of the barbell as physically possible. This was chosen so as to i) avoid sensor and athlete contact and ii) be in a position that was repeatable for each individual based on their preferred snatch grip. Fritschi and colleagues [21] reported similar findings to ours, where the peak velocity standard error of estimate was 0.03 m/s when compared to that of barbell CoM velocity determined by each criterion. These findings collectively suggest that the placement of the Enode anywhere within the barbell collar would enable an accurate representation of barbell CoM peak velocity. This is an important finding to highlight given that the barbell will flex during heavy lifts and it is posited that the peak velocity of the barbell end relative to the center can display a 5–30% difference for the clean [40], although this may likely be less for the snatch due to the lower loads and wider grip, thus creating less barbell deformation. Practically, this highlights that, in some situations, the Enode may potentially be a better option than traditional video analysis where the viewing angle and barbell deformation may affect the outputs generated [40].

It is worth noting that the velocity identified at the end of each key phase of the lift (first pull, transition, and second pull) measured by the Enode showed excellent within- and between-session reliability, with SEMs of 0.00 m/s and SDD values no greater than 0.01 m/s. The current results are supported by the findings from Sandau and colleagues [14], who found that, in elite German weightlifters, the variability (as measured by SEM) of vertical velocity at the end of each lifting phase was smaller than within time-series-measured phases. This may suggest that weightlifters utilize varied strategies between phases to elicit similar outcomes at the end of each phase, thus leading to discreet measures of velocity being highly reliable. Furthermore, Sandau [14] also reported that the transition phase carried the greatest variability, relative to all other end-of-phase velocities. The relevance of obtaining the velocity at the end of each phase is its potential use for identifying the key limiting phase within the lift using a load–velocity profile. Research by Sandau and Granacher [25] on elite German weightlifters reported that a regression slope with the greatest negative value plotted across ascending loads could help identify the phase where the greatest loss of velocity occurs between each phase. Their study utilized a previously validated, bespoke video capture software [41], which is inaccessible to most coaches. Along with the present findings, the implementation of the load–velocity profiling methods presented by Sandau and Granacher [25] to identify limitations in technique can now be widely adopted utilizing a commercial IMU sensor with minimal time constraints.

While velocity is often the focal point of assessment, with the emergence of new technologies, a novel aspect of this investigation was to also assess vertical and horizontal displacements, which are commonly reported within weightlifting analysis research [1,12,16]. Our results indicate that the Enode typically overestimates horizontal displacement with fixed or proportional bias, with large levels of variability present. Interestingly, the present findings seem to report similar SEM's to those presented by Sandau, Langen, and Nitzsche [14], even though different devices were used to capture the data in these studies. These are important findings, as it has been posited that horizontal displacement and its associated measures, such as the loop of the barbell, are key factors between successful and unsuccessful attempts in the snatch [1]. Conceptually, this makes sense, as the further the bar is from the applied center of pressure and athlete CoM, the greater difficulty the athlete will have applying the necessary forces to accelerate the barbell [24]. However, it should be noted that the extremely large variability observed in measures of horizontal displacement means it should not be used to monitor technical changes as the present findings suggests and we would, therefore, suggest it is simply used as a heuristic within the coaching environment.

While this study has provided some practically useful results, it is not without its limitations. Firstly, only 85% 1RM snatches were analyzed. Although a commonly utilized intensity, particularly during heavier periods of training, it is not uncommon for loads to be used between 70 and 90% [42]; therefore, the variability reported in the current study could change with load. This is highlighted by the findings of Sandau, Lanen, and Nitzsche [14], who compared the reliability of various barbell waveforms (displacement, velocity, and acceleration) at 85% and 97% in elite German weightlifters. Their findings suggested that the trial-to-trial variability at submaximal intensities was greater than that near the maximum, suggesting submaximal loads may require less precision to achieve the intended outcome compared to maximal intensities. This highlights that future research may wish to investigate differences in waveforms or discreet measures of displacement, velocity, and acceleration across varying loads to better understand the variability exhibited at a range of loads. This would help highlight which phase(s) of the lift is a potential limiting factor that needs addressing as heavier loads are lifted.

Although the practicality of the Enode holds high ecological validity within training, it is less useful in competition, as nothing is allowed to be attached to the barbell. This is where video capture has a distinct advantage, although one must consider the utility of video cameras in a training environment, along with appropriate software against a commercial IMU system. In the same instance, both methods would require standardized methods of identifying the key phases of the lift. The present study utilized changes in knee joint angle, objectively identified in the criterion analysis. However, this was not possible using the video captured by the Enode's native application. Therefore, some discrepancies within and between raters must also be investigated to ensure consistency in manual phase identification. Lastly, it should be noted that the Enode integrates acceleration collected from the accelerometer; this method of derivation differs from the criterion that collects the coordinates of each marker, which provides displacement. This displacement is then differentiated to obtain velocity and acceleration. It is unlikely that this would contribute to large differences between methods; however, signal noise is often attenuated when integrating acceleration [43], and with small SEMs presented in the current investigation, this cannot be discounted if utilizing any of the proposed measures for monitoring purposes.

5. Conclusions

This study confirms the validity of the Enode and its software in the measure of barbell mechanics during the snatch. The Enode provides both valid and reliable measures of velocity and vertical displacements, with a majority of bias and variance occurring in measures of horizontal displacement. It is important to understand the use of technique analytics must not interfere with the natural ecology of the training environment and that selecting certain times to obtain data is likely more useful and less resource intensive than collecting data day to day. Additionally, given that within-day variability was generally greater than between-session variability, identifying key points within the training cycle to measure changes in technique over time (between sessions) would pay greater dividends than monitoring within sessions (between repetitions). Coaches interested in analyzing and tracking the metrics that the current study shows to be reliable and valid in a training environment could use the Enode device with confidence, although we would urge some caution when loads different to those considered in the current study are used.

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References

1. Stone, M.H.; O'Bryant, H.S.; Williams, F.E.; Johnson, R.L.; Pierce, K.C. Analysis of bar paths during the snatch in elite male weightlifters. *Strength Cond. J.* **1998**, *20*, 30–38.
2. Gourgoulis, V.; Aggeloussis, N.; Garas, A.; Mavromatis, G. Unsuccessful vs. successful performance in snatch lifts: A kinematic approach. *J. Strength Cond. Res.* **2009**, *23*, 486–494.
3. Mastalerz, A.; Szyszka, P.; Grantham, W.; Sadowski, J. Biomechanical analysis of successful and unsuccessful snatch lifts in elite female weightlifters. *J. Hum. Kinet.* **2019**, *68*, 69–79. [PubMed]
4. Nagao, H.; Kubo, Y.; Tsuno, T.; Kurosaka, S.; Muto, M. A biomechanical comparison of successful and unsuccessful snatch attempts among elite male weightlifters. *Sports* **2019**, *7*, 151. [CrossRef]
5. Nagao, H.; Huang, Z.; Kubo, Y. Biomechanical comparison of successful snatch and unsuccessful frontward barbell drop in world-class male weightlifters. *Sports Biomech.* **2023**, *22*, 1120–1135. [PubMed]
6. Kauhanen, H.; Häkkinen, K.; Komi, P.V. A biomechanical analysis of the snatch and clean and jerk techniques of Finnish elite and district level weightlifters. *Scand. J. Med. Sci. Sports* **1984**, *6*, 47–56.
7. Burdett, R.G. Biomechanics of the snatch technique of highly skilled and skilled weightlifters. *Res. Q. Exerc. Sport* **1982**, *53*, 193–197.
8. Liu, G.; Fekete, G.; Yang, H.; Ma, J.; Sun, D.; Mei, Q.; Gu, Y. Comparative 3-dimensional kinematic analysis of snatch technique between top-elite and sub-elite male weightlifters in 69-kg category. *Heliyon* **2018**, *4*, e00658.
9. Campos, J.; Poletaev, P.; Cuesta, A.; Pablos, C.; Carratalá, V. Kinematical analysis of the snatch in elite male junior weightlifters of different weight categories. *J. Strength Cond. Res.* **2006**, *20*, 843–850.
10. Garhammer, J. Power production by Olympic weightlifters. *Med. Sci. Sports Exerc.* **1980**, *12*, 54–60. [PubMed]
11. Antoniuk, O.; Pavlyuk, O.; Chopyk, T.; Pavlyuk, Y. Characteristics of barbell trajectory in snatch, fulfilled by elite female weightlifters. *Pedagog. Psychol. Med.-Biol. Probl. Phys. Train. Sports* **2016**, *20*, 4–8.
12. Musser, L.; Garhammer, J.; Rozenek, R.; Crussemeyer, J.; Vargas, E. Anthropometry and barbell trajectory in the snatch lift for elite women weightlifters. *J. Strength Cond. Res.* **2014**, *28*, 1636–1648. [PubMed]
13. Cunanan, A.J.; Hornsby, G.W.; South, M.A.; Ushakova, K.P.; Mizuguchi, S.; Sato, K.; Pierce, K.C.; Stone, M.H. Survey of barbell trajectory and kinematics of the snatch lift from the 2015 world and 2017 Pan-American weightlifting championships. *Sports* **2020**, *8*, 118. [CrossRef]
14. Sandau, I.; Langen, G.; Nitzsche, N. Variability of time series barbell kinematics in elite male weightlifters. *Front. Sports Act. Living* **2023**, *13*, 1264280.
15. Vorobyev, A.N. *A Textbook on Weightlifting*; International Weightlifting Federation: Budapest, Hungary, 1978.
16. Isaka, T.; Okada, J.; Funato, K. Kinematic analysis of the barbell during the snatch movement of elite Asian weightlifters. *J. Appl. Biomech.* **1996**, *12*, 508–516.
17. Sato, K.; Sands, W.A.; Stone, M.H. The reliability of accelerometery to measure weightlifting performance. *Sports Biomech.* **2012**, *11*, 524–531. [PubMed]
18. Kipp, K.; Harris, C. Patterns of barbell acceleration during the snatch in weightlifting competition. *J. Sports Sci.* **2015**, *33*, 1467–1471.
19. Sandau, I.; Chaabene, H.; Granacher, U. Concurrent validity of barbell force measured from video-based barbell kinematics during the snatch in male elite weightlifters. *PLoS ONE* **2021**, *16*, e0254705.
20. Menrad, T.; Edelmann-Nusser, J. Validation of velocity measuring devices in velocity-based strength training. *Int. J. Comput. Sci. Sport* **2021**, *20*, 106–118.
21. Fritschi, R.; Seiler, J.; Gross, M. Validity and effects of placement of velocity-based training devices. *Sports* **2021**, *9*, 123. [CrossRef]
22. Bazyler, C.D.; Mizuguchi, S.; Zourdos, M.C.; Sato, K.; Kavanaugh, A.A.; DeWeese, B.H.; Breuel, K.F.; Stone, M.H. Characteristics of a national level female weightlifter peaking for competition: A case study. *J. Strength Cond. Res.* **2018**, *32*, 3029–3038. [PubMed]
23. McKay, A.K.; Stellingwerff, T.; Smith, E.S.; Martin, D.T.; Mujika, I.; Goosey-Tolfrey, V.L.; Sheppard, J.; Burke, L.M. Defining training and performance caliber: A participant classification framework. *Int. J. Sports Physiol. Perform.* **2021**, *17*, 317–331.
24. Chavda, S.; Hill, M.; Martin, S.; Swisher, A.; Haff, G.G.; Turner, A.N. Weightlifting: An applied method of technical analysis. *Strength Cond. J.* **2021**, *43*, 32–42.
25. Sandau, I.; Granacher, U. Effects of the barbell load on the acceleration phase during the snatch in elite Olympic weightlifting. *Sports* **2020**, *8*, 59. [CrossRef]
26. Garhammer, J. A Review of Power Output Studies of Olympic and Powerlifting: Methodology, Performance Prediction, and Evaluation Tests. *J. Strength Cond. Res.* **1993**, *7*, 76–89.
27. Lin, L.I.K. A concordance correlation coefficient to evaluate reproducibility. *Biometrics* **1989**, *45*, 255–268.
28. McBride, G.B. A proposal for strength-of-agreement criteria for Lin's concordance correlation coefficient. *NIWA Client Rep.* **2005**, *45*, 307–310.

29. Passing, H.; Bablok, W. A new biometrical procedure for testing the equality of measurements from two different analytical methods. Application of linear regression procedures for method comparison studies in clinical chemistry, Part I. *J. Clin. Chem. Biochem.* **1983**, *21*, 709–720.
30. Lake, J.P.; Mundy, P.D.; Comfort, P.; Suchomel, T.J. Do the peak and mean force methods of assessing vertical jump force asymmetry agree? *Sports Biomech.* **2018**, *19*, 227–234. [PubMed]
31. Koo, T.K.; Li, M.Y. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J. Chiropr. Med.* **2016**, *15*, 155–163.
32. Weir, J.P. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J. Strength Cond. Res.* **2005**, *19*, 231–240. [PubMed]
33. Bernards, J.R.; Sato, K.; Haff, G.G.; Bazyler, C.D. Current research and statistical practices in sport science and a need for change. *Sports* **2017**, *5*, 87. [CrossRef] [PubMed]
34. Cohen, J. *Statistical Power Analysis for the Behavioural Sciences*; Routledge Academic: New York, NY, USA, 1988.
35. Feuerbacher, J.F.; Jacobs, M.W.; Dragutinovic, B.; Goldmann, J.P.; Cheng, S.; Schumann, M. Validity and test-retest reliability of the Vmaxpro sensor for evaluation of movement velocity in the deep squat. *J. Strength Cond. Res.* **2023**, *37*, 35–40.
36. Dragutinovic, B.; Jacobs, M.; Feuerbacher, J.; Goldmann, J.P.; Cheng, S.; Schumann, M. Evaluation of the Vmaxpro sensor for assessing movement velocity and load-velocity variables: Accuracy and implications for practical use. *Biol. Sport* **2023**, *41*, 41–51.
37. Olaya-Cuartero, J.; Villalón-Gasch, L.; Penichet-Tomás, A.; Jimenez-Olmedo, J.M. Validity and Reliability of the VmaxPro IMU for back squat exercise in multipower machine. *J. Phys. Educ. Sport* **2022**, *22*, 2920–2926.
38. Villalon-Gasch, L.; Jimenez-Olmedo, J.M.; Olaya-Cuartero, J.; Pueo, B. Test–Retest and Between–Device Reliability of Vmaxpro IMU at Hip and Ankle for Vertical Jump Measurement. *Sensors* **2023**, *23*, 2068. [CrossRef] [PubMed]
39. Jimenez-Olmedo, J.M.; Pueo, B.; Mossi, J.M.; Villalon-Gasch, L. Concurrent validity of the inertial measurement unit VmaxPro in vertical jump estimation. *Appl. Sci.* **2023**, *13*, 959. [CrossRef]
40. Chiu, L.Z.; Schilling, B.K.; Fry, A.C.; Salem, G.J. The influence of deformation on barbell mechanics during the clean pull. *Sports Biomech.* **2008**, *7*, 260–273.
41. Sandau, I.; Jentsch, H.; Bunk, M. Realanalyzer HD—A real-time barbell tracking software for weightlifting. *EWF Sci. Mag.* **2019**, *5*, 14–23.
42. Medvedyev, A.S. *A System of Multi-Year Training in Weightlifting*; Fizkultura I Sport: Moscow, Russia, 1989.
43. Lake, J.; Augustus, S.; Austin, K.; Comfort, P.; McMahon, J.; Mundy, P.; Haff, G.G. The reliability and validity of the bar-mounted PUSH Band^{TM} 2.0 during bench press with moderate and heavy loads. *J. Sports Sci.* **2019**, *37*, 2685–2690.