# VELOCITY BASED STRENGTH TRAINING: VALIDITY OF THE APPLE WATCH 7 TO MEASURE MOVEMENT VELOCITY IN THE BACK SQUAT

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Velocity-Based resistance Training (VBT) measurement methods based on commercially-available electronics in smartphones and other wearables are not yet accessible to the broad public. Building on this gap, the motivation for this study was to assess the validity of the Apple Watch 7 for broad application to VBT. In particular, the velocity predictions of a barbell mounted Apple Watch 7 were compared against data from 3D optical motion capture (Vicon) as gold standard in 22 subjects for the free weight back squat. The subjects reported to the lab for one testing session and performed the free weight back squat at intensities between 45 and 100 percent of their one-repetition-maximum. A total of 574 repetitions (total), 285 repetitions (slow), 289 repetitions (fast) were successfully recorded, with only 30 repetitions missing because of connection issues between the Apple Watch and the server infrastructure. The peak and mean velocity predictions of the concentric movement phase were with a high precision compared to Vicon (Vmean: SEE=0.049m/s, r=0.976, Vpeak: 0.092m/s, r=0.959), with the error being similar or smaller compared to other validation studies. The insight gained in this work plays a crucial part toward advancing VBT monitoring technologies for broader use by demonstrating the validity of commercially-available and highly popular consumer electronics.

**KEYWORDS:** VELOCITY-BASED TRAINING, RESISTANCE TRAINING MONITORING, BARBELL KINEMATICS, WEARABLE, IMU

**INTRODUCTION:** It is widely known that Resistance Training (RT) improves the performance of athletes, allowing them to potentiate earlier and have a lower risk of injury. RT has also been shown to offer promising benefits in many areas of daily life, however, one challenge with RT is to objectively monitor neuromuscular fatigue and actual workload to ensure compliance with RT guidelines, maximise training benefits and minimise the risk of injury. Here, Velocity-Based Training (VBT) offers a promising objective method for monitoring RT to ensure safety and efficiency of training outcome. Yet, a major challenge of VBT is the need for a measuring device to assess lifting velocity. For this reason, recent studies have analysed the validity and reliability of affordable technologies used to measure barbell velocity during RT such as high-speed cameras, smartphone applications, or wearable devices (4,10). However, VBT measurement methods based on commercially-available electronics in smartphones and other wearables are not yet accessible to the broad public audience because of a lack of scientifically validated products. Building on this gap, the motivation for this study was to assess the validity of the Apple Watch 7 for broad application to VBT monitoring.

**METHODS:**
The participants in the present study were 22 recreationally active RT athletes with at least 3 years of experience in the free weight back squat (n=12M/10F, age = 29.1 ± 5.2, height = 1.65 ± 0.4 m; body mass = 77.5 ± 12.6 kg; back squat 1RM = 134.2 ± 32.1 kg). The study protocol complied with the Declaration of Helsinki for Human Experimentation and was approved by the regional ethics committee. Written informed consent was obtained from each participant prior to data acquisition. The study design was developed to assess the validity of the Apple Watch 7's Inertial Measurement Unit (IMU) sensor (Apple Inc., Cupertino, CA, USA) during the free weight back squat. Subjects reported to the lab for one testing session, where they performed back squats between 45 to 100 percent of their One-Repetition Maximum (1RM) at maximum voluntary lifting velocity according to VBT guidelines.
The velocity of the barbell was measured using a barbell mounted Apple Watch and an optical 3D motion capture system (Vicon 3D Motion Systems, Oxford, United Kingdom), both measuring at 100Hz. Thereby, two reflective markers were attached on both ends of the barbell

and tracked using 10 infrared cameras, while the Apple Watch was attached next to the left hand of the subject. A 4th order Butterworth filter was used to smooth all the data. Vertical lifting velocity was calculated by integrating the acceleration data from the Apple Watch over time, and differentiating the position from the reflective markers, respectively. All Vicon cameras were controlled from an Antec WorkBoy desktop (Antec, Taipei, Taiwan) running Vicon Nexus software (version 2.9, Vicon Motion Systems Ltd., Oxford, UK), while a custom iOS application was written to facilitate data acquisition with the Apple Watch. The concentric velocity phase of the back squat was defined in line with RT guidelines to start at the lowest vertical position (turning point) and end at the point the velocity reached zero (end position of squat).

Vicon was considered the reference “criteria” in this study. The validity of the Apple Watch was assessed against the criteria for mean (Vmean) and peak (Vpeak) velocity separately using the three-tier approach recommended by Hopkins (5) comprising of a Pearson’s correlation coefficient (r), a calibration equation, and the Standard Error of the Estimate (SEE). This analysis was done for 1) the whole velocity spectrum, 2) repetitions with concentric criterion duration below 1.25s, and 3) concentric criterion duration above and equal 1.25s categorized into “total”, “slow” and “fast”, respectively. The time threshold was chosen accordingly to build two similar sized groups with two velocity spectrums (slow and fast).

For the calibration equation, Ordinary Least Product (OLP) regression was used (8), as both criterion and Apple Watch measurement were subject to random measurement errors. The SEE was calculated from residuals of the OLP calibration equation according to Siegel (13) and Fritschi et. al. (4). Correlation coefficients were interpreted with lower thresholds of 0.5, 0.7, and 0.9 for large, very large, and extremely large, respectively (6). According to Fritschi et. al. (4), the absolute SEE was interpreted by supposing a meaningful thresholds of 0.1 m/s as high, which would be adequate for identifying a 30% velocity loss at relatively high loads. Proportional measurement bias was considered to exist if the 95% confidence limits of the calibration slope did not include One, while a fixed measurement bias was considered to exist if the 95% confidence limits of the calibration intercept did not include Zero (8).

For a better comparison with existing publications, the Inter Correlation Coefficient (ICC 3.1) values were also included to test agreement between measurements. Values between 0.8 to 0.9 were considered as good and above > 0.9 as excellent (7). All statistical analysis was performed with Python employing the SciPy and Pingouin libraries.

**RESULTS:** A total of 574 repetitions (total), 285 repetitions (slow), 289 repetitions (fast) of the free weight back squat were successfully recorded in the 22 participants, with only 30 repetitions missing caused by connection issues between the Apple Watch and the server.

***Accuracy***: The main indicators for accuracy are displayed in Table 1 as the slope and intercept of the calibration equation with a 95% confidence interval, whereas Figure 1 visualizes the calibration equation for the whole velocity spectrum. For Vmean(total), a small proportional bias is revealed (slope=1.003-1.04). A larger proportional bias was found (slope=1.086-1.138) for Vpeak(total), which is apparent throughout the entire velocity spectrum (slow and fast repetitions).

***Precision***: The indicators for precision are displayed in Table 1 in the form of the SEE and the Pearson’s r. For all velocity parameters, the SEE was rated ‘low’ with values between 0.036 – 0.092 m/s. Furthermore, all combinations showed extremely large correlations (0.924-0.979), except for Vmean(slow) and Vpeak(fast) which still showed large correlations (0.888-0.934). These findings are supported by the ICC values which confirm the agreement between measurements. No clear effect was revealed by the two velocity groups (slow, fast) expect that slow repetitions yielded a slightly worse relative precision (SEE%= 9.4% and 7.3%) compared to faster repetitions (SEE% = 8.1% and 6.6%).

**DISCUSSION:** This study aimed at assessing the validity of the Apple Watch 7 in VBT monitoring of the free weight back squat. Similar levels of accuracy and precision were previously reported for IMU based VBT devices such as the Beast Sensor (Beast Technologies S.r.l., Brescia, Italy), VmaxPro (BM Sports Technology GmbH, Magdeburg, Germany) and Push Band 2 (Whoop, Boston, United State of America) (3,4). In particular, Balsalobre et al. (1) found the Beast wearable device to have acceptable validity (Vmean: r = 0.973–0.983, SEE = 0.05 m/s) . Mitter et al (9) also validated the Beast wearable device (Vmean: r = 0.95, SEE = 0.110-0.124, Vpeak: r =0.84 , SEE = 0.166-0.188), as well as the Push Band 2 (Vmean: r =

0.97, SEE = 0.073-0.083, Vpeak:  r = 0.92, SEE = 0.130–0.146). Both devices were rated valid by the authors, which was confirmed by Clemente et al (2) in a systematic review. Additional, Fritschi et al. assessed the validity of the VmaxPro (Vmean: SEE = 0.02–0.13, Pearson's r = 0.94–0.96, Vpeak: SEE = 0.07–0.08, Pearson's r = 0.92–0.99 ranking it among the most  valid VBT devices on the market.  Because of the revealed high precision and high agreement, the calibration equations could be used to correct for both proportional and fixed biases in a post-processing step.

**Table 1: Validity indicators for  mean and peak velocity parameters (V mean and V peak, respectively). Slope and intercept were generated using least-product linear regression. SEE: standard error of estimate from least-product linear regression. ICC: intraclass correlation coefficient. Values between brackets represent 95% confidence interval. Time value (t) refers to the concentric part of repetition.**

| | | Slope | Intercept | SEE ($ms^{-1}$,%) | Pearson's r | ICC 3.1 |
|---|---|---|---|---|---|---|
| V mean | slow (t>=1.25s) | 0.945 [0.900, 0.992] | 0.031 [0.012, 0.050] | 0.040 9.4% | 0.910 [0.888, 0.928] | 0.909 [0.886, 0.927] |
| | fast (t<1.25s) | 1.020 [0.980, 1.062] | 0.005 [-0.027, 0.035] | 0.055 7.0% | 0.939 [0.924, 0.951] | 0.939 [0.924, 0.951] |
| | total | 1.022 [1.003, 1.040] | 0.002 [-0.009, 0.012] | 0.049 8.1% | 0.976 [0.971, 0.979] | 0.975 [0.971, 0.979] |
| V peak | slow (t>=1.25s) | 1.324 [1.274, 1.376] | -0.156 [-0.204, -0.110] | 0.078 7.3% | 0.944 [0.930, 0.955] | 0.908 [0.885, 0.927] |
| | fast (t<1.25s) | 1.106 [1.056, 1.158] | 0.014 [-0.056, 0.081] | 0.099 6.6% | 0.918 [0.898, 0.934] | 0.913 [0.892, 0.931] |
| | total | 1.112 [1.086, 1.138] | 0.023 [-0.007, 0.052] | 0.092 7.1% | 0.959 [0.952, 0.965] | 0.954 [0.946, 0.96] |

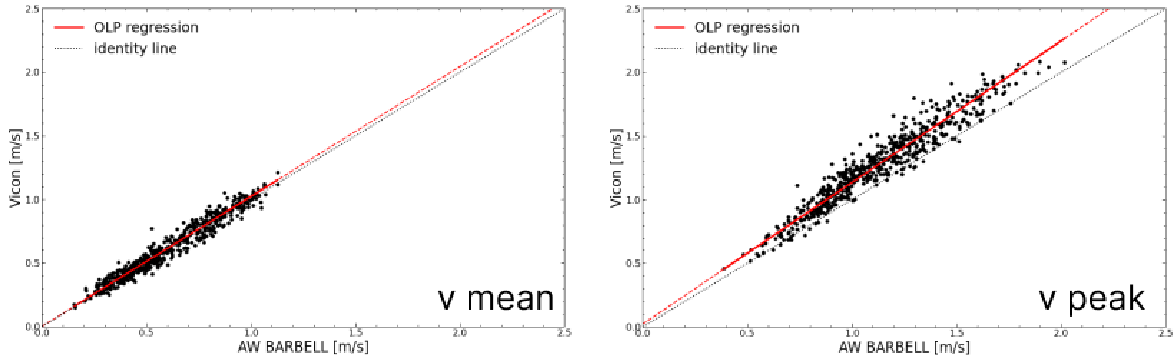


**Figure 1 Calibration equation between Apple Watch and criterion (Vicon) for mean (left) and peak (right) velocity of the total amount of repetitions (n=574).**

Here the Apple Watch resembles a popular wearable with a large user base and a broad variety of features not restricted to a certain activity such as RT or VBT. As such, it could reduce the burden to buy a device for the sole purpose of VBT. Therefore, the Apple Watch has the potential to provide a minimalistic, reasonable priced VBT device which, with an appropriate iOS app, is highly user friendly. This is important to remember, as validity is not the only criterion for a VBT device.

Because a trend for an overestimation at higher mean velocities was reported for the VmaxPro and the BeastSensor (3,11), we splitted the present analysis into two similar sized groups with different velocity spectrums (slow, fast), as described in the methods. No clear effect was revealed by the different velocity spectrums expect that slow repetitions yielded a slightly worse relative SEE values compared to faster repetitions. This results in a slightly higher validity for the fast repetitions when focusing on relative SEE, as absolute SEE values tend to increase with higher velocities. This might result from the accumulation of drift produced by the IMU itself, which represents a major challenge in IMU measurements (12). These results stand in contrast to reported results for the VmaxPro and Beast Sensor (3,11) but are in line with the Push Sensor (11). Therefore, it is important to consider that 1) different IMU's might have different reading and sources of errors from the hardware side and 2) because scarce information about the embedded algorithms in commercially-available sensors is available, little can be concluded about possible error sources from the software side. However, in the present work the raw data was used to derive the velocity parameters which gives full control from the software side. We highly agree with Mitter's (9) recommendation to treat results of investigations with caution, as companies tend to adapt their hard- and software constantly.

Nevertheless, in this work we found the barbell mounted Apple Watch 7 valid for deriving the mean and peak velocity of the concentric part of the free weight back squat. If these results can be confirmed by others this would lead to a new valid VBT tool with high potential regarding the popularity of the Apple Watch.

**CONCLUSION:** The findings of this study provide a rationale on the use of the Apple Watch 7 to assess movement velocity during VBT. It adds value to the VBT community as the Apple Watch is a popular wearable device already used by many with a broad variety of features not restricted to VBT. Furthermore, the Apple Watch resembles a minimalistic, reasonable priced VBT device which, with an appropriate iOS app, is highly user friendly. This is important to remember, as validity is not the only important criterion for a VBT device. A slightly higher validity was found for fast repetitions, which should be investigated in further studies as it suggests a higher accumulating drift effect for slower repetitions. Other validation studies of IMU-based VBT devices have not reported this behaviour and it is not yet clear if it is hardware or software caused. To the best of our knowledge this is the first study demonstrating that the barbell mounted Apple Watch 7 is a valid device to assess movement velocity during the free weight back squat exercise.

**REFERENCE:**


1. Balsalobre-Fernández, C, Marchante, D, Baz-Valle, E, Alonso-Molero, I, Jiménez, SL, and Muñóz-López, M. Analysis of Wearable and Smartphone-Based Technologies for the Measurement of Barbell Velocity in Different Resistance Training Exercises. *Front Physiol* 8: 649, 2017.
2. Clemente, FM, Akyildiz, Z, Pino-Ortega, J, and Rico-González, M. Validity and Reliability of the Inertial Measurement Unit for Barbell Velocity Assessments: A Systematic Review. *Sensors* 21: 2511, 2021.
3. Feuerbacher, JF, Jacobs, MW, Dragutinovic, B, Goldmann, J-P, Cheng, S, and Schumann, M. Validity and Test-Retest Reliability of the Vmaxpro Sensor for Evaluation of Movement Velocity in the Deep Squat. *Journal of Strength and Conditioning Research* Publish Ahead of Print, 2022.Available from: https://journals.lww.com/10.1519/JSC.0000000000004207
4. Fritschi, R, Seiler, J, and Gross, M. Validity and Effects of Placement of Velocity-Based Training Devices. *Sports* 9: 123, 2021.
5. Hopkins, WG. A New View of Statistics: Measures of Validity. , 2000.Available from: https://www.sportsci.org/resource/stats/precision.html
6. Hopkins, WG, Marshall, SW, Batterham, AM, and Hanin, J. Progressive Statistics for Studies in Sports Medicine and Exercise Science. *Medicine & Science in Sports & Exercise* 41: 3–12, 2009.
7. Koo, TK and Li, MY. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine* 15: 155–163, 2016.
8. Ludbrook, J. Linear regression analysis for comparing two measurers or methods of measurement: But which regression?: Linear regression for comparing methods. *Clinical and Experimental Pharmacology and Physiology* 37: 692–699, 2010.
9. Mitter, B, Hölbling, D, Bauer, P, Stöckl, M, Baca, A, and Tschan, H. Concurrent Validity of Field-Based Diagnostic Technology Monitoring Movement Velocity in Powerlifting Exercises. *Journal of Strength and Conditioning Research* 35: 2170–2178, 2021.
10. Oberhofer, K, Erni, R, Sayers, M, Huber, D, Lüthy, F, and Lorenzetti, S. Validation of a Smartwatch-Based Workout Analysis Application in Exercise Recognition, Repetition Count and Prediction of 1RM in the Strength Training-Specific Setting. *Sports* 9: 118, 2021.
11. Pérez-Castilla, A, Piepoli, A, Delgado-García, G, Garrido-Blanca, G, and García-Ramos, A. Reliability and Concurrent Validity of Seven Commercially Available Devices for the Assessment of Movement Velocity at Different Intensities During the Bench Press. *Journal of Strength and Conditioning Research* 33: 1258–1265, 2019.
12. Seel, T, Kok, M, and McGinnis, RS. Inertial Sensors—Applications and Challenges in a Nutshell. *Sensors* 20: 6221, 2020.
13. Siegel, AF. Correlation and Regression. In: Practical Business Statistics.Elsevier, 2016 [cited 2022 Jan 12]. pp. 299–354Available from: https://linkinghub.elsevier.com/retrieve/pii/B9780128042502000110


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