Validation of Velocity Measuring Devices in Velocity Based Strength Training

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Abstract

To control and monitor strength training with a barbell various systems are on the consumer market. They provide the user with information regarding velocity, acceleration and trajectory of the barbell. Some systems additionally calculate the 1-repetition-maximum (1RM) of exercises and use it to suggest individual intensities for future training. Three systems were tested: GymAware, PUSH Band 2.0 and Vmaxpro. The GymAware system bases on linear position transducers, PUSH Band 2.0 and Vmaxpro base on inertial measurement units. The aim of this paper was to determine the accuracy of the three systems with regard to the determination of the average velocity of each repetition of three barbell strength exercises (squat, barbell rowing, deadlift). The velocity data of the three systems were compared to a Vicon system using linear regression analyses and Bland-Altman-diagrams.

In the linear regression analyses the smallest coefficient of determination (R^2) in each exercise can be observed for PUSH Band 2.0. In the Bland-Altman diagrams the mean value of the differences in the average velocities is near zero for all systems and all exercises. PUSH Band 2.0 has the largest differences between the Limits of Agreement. For GymAware and Vmaxpro these differences are comparable.

KEYWORDS: VELOCITY BASED TOOLS, VICON, PUSH, GYMAWARE, VMAXPRO

Introduction

To improve control of strength training with a barbell, various systems have been on the market for several years. The user is provided with information regarding velocity, acceleration, and trajectory. Occasionally, suppliers suggest individual intensities according to the objective and depending on the athlete's performance. In this context, said systems are used in various sports such as Olympic weightlifting, rowing, American football or rugby. Since the training loads are determined by the velocities measured by the system, those velocities must be recorded with the appropriate accuracy. This study, based on the publications of Balsalobre-Fernández et al. (2017) and Lorenzetti et al. (2017), questions the accuracy of three current velocity tracking systems in strength training:

- Linear position transducers have already been on the market for several years and have been evaluated several times in different areas of strength training (Lorenzetti et al., 2017). A very widespread system is GymAware (Figure 1) manufactured by the company Kinetic Performance Technology (Mitchell, AUS).
- Systems based on inertial measurement units (IMUs) in combination with mobile phones or tablets show a high mobility and simplicity of use, but to determine the velocity a calculation of the integral of the acceleration, which is directly measured, is necessary. These calculations of the integral may lead to inaccurate determinations of the velocities. Compared to linear position transducers, the main advantage is the lack of a need for a cable pulley system to collect data. Instead, the system is attached directly to the bar.

One of the systems that is based on the measuring principle of inertial sensors is PUSH Band 2.0 manufactured by the company PUSH Design Solutions Inc. (Toronto, Canada). Another product that has not yet been investigated in scientific studies is Vmaxpro manufactured by the company Blaumann & Meyer - Sports Technology UG (Magdeburg, Germany) (Figure 1).

GymAware has been on the market for many years and has seen extensive use for both training and research purposes (Cronin, Jones, & Hagstrom, 2007; Drinkwater, Pritchett, & Behm, 2007; Harries, 2014; Koefoed et al., 2018; Mann, 2015; Turner, n.d.; Walker, 2017) and has been described as the gold standard among linear position sensors (GymAware, n.d.). The validity and reliability of GymAware have been put to the test (Youngson, 2010). The system uses a cable pulley system with an additional protractor (GymAware, n.d.): The cable pulley system is used to measure the total extension (distance) (see Figure 1). The vertical component of the total extension is then calculated using the protractor. Velocity data can be determined accordingly via the derivative with respect to time.

Inertial measurement units utilize accelerometers and gyroscopes. They record three-dimensional acceleration data. Velocity and distance data can be calculated by integrating the acceleration data. According to the manufacturer's specifications, the product PUSH Band 2.0 can be worn on the barbell (see Figure 1) as well as on the athlete's arm or hip. Balsalobre-Fernández, Kuzdub, Poveda-Ortiz, & Campo-Vecino (2016) evaluated PUSH Band 1.0 as a valid system suitable for use in training after examining a squat with a smith machine. A further examination of PUSH Band 1.0 with the choice of a dumbbell shoulder press resulted in deviations of 12.6% in the average velocity and 14.0% in the determined maximum velocity compared to the 3D kinemetry system Vicon (Sato et al., 2015). Banyard et al. (2017) described the validity of PUSH Band 1.0 in the determination of maximum and average velocity after the examination of the squat as questionable. The product Vmaxpro has been on the market for over 4 years, primarily in competitive sports. The sensor is magnetic and is placed directly on the barbell. Alternatively, it can be attached to the barbell in a small pocket

with a velcro fastener (see Figure 1). The company's internal validity studies can be found on their website (Blaumann & Meyer - Sports Technology UG, n.d.) and show that Vmaxpro has a high level of validity and reliability for snatch, bench press, deadlifts and squats.

Figure 1: Attaching the GymAware, Vmaxpro and PUSH Band 2.0 systems to a barbell. PUSH Band 2.0 and Vmaxpro are each located in small pockets attached to the barbell by a velcro fastener.

All three systems described provide data on the average and maximum velocity and the power output of each individual repetition of an exercise. The systems evaluate the data automatically. Only GymAware provides insight and/or an export option for (down-sampled) raw data. Based on the velocity data, all three systems also forecast the 1-repetition maximum (1RM, maximum load at which an exercise can be performed exactly for one repetition across the full range of motion) of the exercises, which is used as a variable for load control (Jovanović, & Flanagan, 2014; Thompson, Rogerson, Ruddock, & Barnes, 2020). This is possible even with loads significantly below the 1RM. This is based on the linear relationship between load and movement velocity (Jovanović, & Flanagan, 2014). With increasing load, the speed of concentric muscle contraction decreases (Cronin, McNair, & Marshall, 2003; González-Badillo, & Sánchez-Medina, 2010; Jidovtseff, Harris, Crielaard, & Cronin, 2011; Sanchez-Medina, Perez, & Gonzalez-Badillo, 2010). The relationship can be described by a simple linear regression (Jovanović, & Flanagan, 2014):

$$Load = m \cdot Velocity + c. \quad (1)$$

$m \left[\frac{\text{kg} \cdot \text{s}}{\text{m}} \right]$ describes the slope, c [kg] the y-intercept of the straight line, $Velocity \left[\frac{\text{m}}{\text{s}} \right]$ the speed, $Load$ [kg] the total load consisting of the barbell plus weights.

The concept of load-velocity-based 1RM estimation requires performing exercises at maximum intended velocity. To determine the 1RM, the "minimum velocity threshold" (MVT) is necessary: The MVT is the lowest mean concentric movement speed with which the last successful repetition of an exercise in a set can still be correctly performed before reaching complete fatigue at maximum effort. The MVT value can be based on empirical values and varies depending on the exercise, i.e. the value for bench press at 0.15m/s is different from the value for squatting at 0.3m/s (Izquierdo et al., 2006; González-Badillo, & Sánchez-Medina, 2010). The load that just allows an exercise to be performed at this average speed is estimated to be the maximum load that the athlete is able to move for one repetition across the full range of motion, i.e. the 1RM (Jovanović, & Flanagan, 2014).

The aim of the investigation was to determine how accurately the three systems GymAware, PUSH Band 2.0 and Vmaxpro determine the average velocity in three common exercises (squat, barbell rowing, deadlift) under conditions similar to the conditions in which they are used in the athletes' training.

Methods

The study was carried out with 12 subjects (1.76 ± 0.07 m, 79.58 ± 5.35 kg, 32.50 ± 5.71 years, 8 male/4 female). The inclusion criteria were the following: At least two years of resistance training experience including squat, barbell rowing and deadlift to ensure technically correct execution of the exercises, strength training at least one time per week in the last year. Further on the subjects had to be of legal age at the time of the examination and had to show no current injuries or movement restrictions. Subjects had to complete three exercises that correspond to their common training exercises. The 1RM of the exercises were determined before the examination. The first exercise were back squats (Figure 2.a), followed by standing bent-over barbell rows (Figure 2.b) and deadlifts (Figure 2.c).

When squatting, a shoulder-wide stance was to be taken, the bar was to be placed on the shoulders and, with a straight back, the subjects had to descend to a position in which their hips were level with their knees. For barbell rowing, the subjects had to bend their knees slightly and bend their upper body forward while keeping their backs straight. The barbell rested in a prone hand position of extended arms and had to be pulled towards the rib cage. During deadlifts, the bar was on the floor in front of the subjects. The subjects had to grip the bar with arms extended and lower their hips to get into starting position. A straight back was essential to avoid injuries. From this position the subjects had to raise the bar by simultaneously extending their hips and knees without bending their arms.

Three sets had to be completed for each exercise. The first and second set contained 10 repetitions each with 40 and 60 % of the 1RM, the third set was performed with 80 % of the 1RM and the subjects were instructed to complete the set one repetition shy of technical failure. Back squats were started from a standing position, the barbell was positioned in the squat stand and was picked up by the subject. Barbell rows began with the bar already held by the subjects with their arms fully extended. During deadlifts, the barbell was on the floor at the start of the exercise. Each set was counted in with the start signal "Ready-Set-Go". In the case of deadlifts, each repetition was individually instructed with a "Go" in order to minimize influences on the systems due to vibrations when the bar was set down. The subjects were instructed to ensure that the exercises were performed technically sound and to work at maximum effort.

The subjects performed the three exercises one after the other on the same day without a rest day for recovery. This is likely to have influenced the velocities of the exercises performed as second and third. These velocities were probably a little lower than they would have been with a rest day between the exercises. But the aim of the study was not to investigate velocities in strength training to optimize training, the aim was to compare the determined velocities of the three systems.

Figure 2: Exercises examined. a squat, b barbell rowing, c deadlift.

A motion capturing system with 12 infrared cameras (Vicon MX T20) was used as a gold standard reference (Richards, 1999). Four passive retroreflective markers were attached to the barbell (see Figure 3 and Figure 1). Two markers were attached to the two ends of the bar, the other two markers were placed opposite each other on the inside of the bar (marked red in Figure 3). The data were recorded with the software Vicon Nexus 2.10, with a frequency of 200 Hz. We applied Woltring filtering routine and exported the data to Matlab. The velocity and the position were calculated using the midpoint of the two markers inside the bar representing the center of the barbell as well as a point close to where the three velocity tracking systems are attached to the barbell. The beginning and the end of a repetition were determined by exceeding or falling below a speed threshold of 0.02 m/s. The exercise was performed on a rubberized training platform, consisting of an adjustable squat stand, a 20 kg barbell, competition weights between 0.5 and 25 kg and two plastic collars for safety.

Figure 3: Schematic measurement setup with four Vicon markers (light blue and red), as well as the Vmaxpro (orange), PUSH Band 2.0 (dark blue) and GymAware (black) systems. The two red markers in the grip area are used to determine the kinematic parameters, the markers at the ends of the barbell are a safeguard in case the determination of the parameters is not possible with the markers in the grip area.

The GymAware Powertool was placed on a weight plate and the cable was attached to the outer end of the barbell, vertically above the main system (see Figures 3 and 1). The PUSH Band 2.0 and Vmaxpro (firmware 6.0.0, hardware version 6.0) were each fastened with a Velcro fastener to the inside of the bar to the right and left of the markers (see Figure 3 and Figure 1). The data from the three measuring systems were recorded with the corresponding measuring software from the manufacturers (Vmaxpro app version 4.0, PUSH app version 4.6.2, GymAware app version 2.6) for iOS and are connected to the end devices via Bluetooth. Vmaxpro works with an output frequency of 200 Hz (information from the manufacturer, 25 April 2020). GymAware works with 50 Hz (GymAware, n.d.). PUSH Band 2.0 acquires data at a frequency of 1000 Hz (PUSH Inc., n.d.).

The acquired data of all systems were exported and linear regressions of the average velocities versus the reference system were plotted for all exercises and separately for squat, barbell rowing and deadlift (see Figure 4). The equations of all linear regressions ($y=mx+b$; b is the bias and m the relative deviation) and the coefficients of determination (R^2) were computed and drawn in Figure 4. Further on the systems were compared via Bland-Altman diagrams (Bland, & Altman, 1999): The differences of mean velocities per repetition of the systems to be evaluated compared to the reference system Vicon (midpoint of the two red markers in Figure 3 representing the center of the barbell as well as a point close to where the three velocity tracking systems are attached to the barbell) were calculated (difference of mean velocities, see Figures 5 to 8) and plotted against the mean values of mean velocities per repetition of Vicon and the respective system (mean of velocities, see Figures 5 to 8). For each system, the mean of the differences (Mean Vmaxpro, Mean GymAware, Mean PUSH Band 2.0; see Figures 5 to 8) was calculated and used as a basis for the evaluation of systematic determination errors. The Limits of Agreement (LoA) of the differences of the mean velocities per repetition, within which approximately 95% of the respective difference values lie, were also determined for each of the three systems and plotted in the Bland-Altman diagrams (see Figures 5 to 8: LoA Vmaxpro, LoA GymAware, LoA PUSH Band 2.0) for all exercises and separately for squat, barbell rowing and deadlift.

Results

Figure 4 shows linear regressions of the average velocities of the three systems versus the reference system for all exercises and for squat, barbell rowing and deadlift. The largest dispersion around the regression line and the smallest R^2 can be observed for PUSH Band 2.0 for all exercises together as well as for squat, barbell rowing and deadlift. The bias b of all three systems for all exercises together is a small value, but PUSH Band 2.0 shows the largest one (0.127m/s). For the three different exercises PUSH Band 2.0 also shows the largest absolute value of the bias each. Also the largest relative deviation m can be observed for PUSH Band 2.0: Nearly 28% (factor 0.7203) in deadlift. The maximum relative deviation of GymAware is about 15% (factor 0.8526) in barbell rowing. In contrast the maximum relative deviation of Vmaxpro is only 2% (factor 0.9804, barbell rowing).

Figures 5 to 8 show the Bland-Altman diagrams of the systems to be evaluated in comparison to the reference system Vicon: Figures 5 to 7 include the data of all three exercises together, Figure 8 shows the Bland-Altman diagrams separately for squat, barbell rowing and deadlift.

GymAware (Figure 5) velocity differences mostly lie in the positive range for each of the three different exercises. This is especially true for higher velocities. Vmaxpro shows mainly negative difference values near zero for all exercises together (Figure 6) and for each of the three different exercises (Figure 8). The mean value of the differences is 0.002 m/s for PUSH Band 2.0 (Figure 7) for all exercises together, 0.024m/s in squat, -0.006m/s in barbell rowing and -0.011m/s in deadlift. However, the distribution for PUSH Band 2.0 is wide and covers a range from -0.34 to 0.34 m/s.

Figure 4: Linear regressions of the average velocities of the three systems versus Vicon. From top to bottom: all exercises together, only squat, only barbell rowing, only deadlift; from the left to the right: GymAware (red), Vmaxpro (yellow), PUSH Band 2.0 (blue).

Figure 5: Bland-Altman diagram of the average velocity of GymAware versus Vicon for all three exercises together. The mean values of the differences of the average velocities and their upper and lower LoA are shown for all three systems. The mean value of the differences Mean GymAware is 0.024 m/s, 1.96 times the standard deviation of the differences is 0.056 m/s.

Figure 6: Bland-Altman diagram of the average velocity of Vmaxpro versus Vicon for all three exercises together. The mean values of the differences of the average velocities as well as their upper and lower LoA are shown for all three systems. The mean value of the differences Mean Vmaxpro is -0.014 m/s, 1.96 times the standard deviation of the differences is 0.043 m/s.

Figure 7: Bland-Altman diagram of the average velocity of PUSH Band 2.0 versus Vicon for all three exercises together. The mean values of the differences of the average velocities and their upper and lower LoA are shown for all three systems. The mean value of the differences Mean PUSH Band 2.0 is 0.002 m/s, 1.96 times the standard deviation of the differences is 0.136 m/s.

Table 1 shows the differences between the upper LoA and the lower LoA of each system in the Bland-Altman diagrams in the Figures 5 to 8. The largest values for these differences can be observed for PUSH Band 2.0 for all exercises together as well as for the three different exercises.

Table 1: Differences between upper LoA and lower LoA of each system in the Bland-Altman diagrams

	GymAware	Vmaxpro	PUSH Band 2.0
all exercises together [m/s]	0.112	0.085	0.272
squat [m/s]	0.050	0.084	0.143
barbell rowing [m/s]	0.133	0.093	0.284
deadlift [m/s]	0.113	0.076	0.335

Figure 8: Bland-Altman diagrams for the three systems GymAware (red), Vmaxpro (yellow), PUSH Band 2.0 (blue) and the three different exercises.

Discussion

In the linear regression analyses, PUSH Band 2.0 has the largest scatter and the smallest values for R^2 for each exercise. Furthermore, relative deviations of up to an average of more than 25% (slopes in the barbell rowing and the deadlift in Figure 4) can be observed for PUSH 2.0, whereas Vmaxpro deviates relatively only up to an average of 2% in the barbell rowing and even less in the other two exercises. The relative deviations of GymAware are up to an average of nearly 15% in the barbell rowing and nearly 11% in the deadlift. Only in the squat GymAware deviates relatively only up to an average of less than 4%. In the Bland-Altman diagrams the mean value of the differences in the average velocities is near zero for all systems and all exercises. PUSH Band 2.0 has the largest differences between the upper LoA and the lower LoA. For GymAware and Vmaxpro the differences between the magnitudes of the LoA intervals in Table 1 are less than or equal to 0.04m/s. The fact that the magnitudes of the LoA intervals for Vmaxpro and GymAware are similar whereby three out of four of these values for Vmaxpro are even slightly lower than those of GymAware is surprising, due to the determination principles used by Vmaxpro (inertial measurement units) and GymAware (linear position transducer): It would have been expected that the velocities from the derivatives of the path data with GymAware would provide more accurate results than those from the integrated acceleration data with Vmaxpro.

The results for PUSH Band 2.0 are worse than those of Vmaxpro and GymAware. Compared to GymAware, this could be attributed to the measuring principle. In comparison with Vmaxpro, however, this is not possible, since both systems use inertial measurement units. The differences can be assumed to lie in the type of sensor technology used, the calibration and the mathematical algorithms of the data processing.

The results for GymAware correspond to the findings of other studies, the results for PUSH Band can only be compared with the studies that used PUSH Band 2.0: Askow et al. (2018) state that GymAware is a valid tool to quantify average velocity: They also used a motion capturing system (Qualysis, 8 cameras) as a gold standard reference. Nine subjects did squats at 75% and 90% of 1RM. In their study GymAware overestimates the average velocities: In their Bland-Altman diagram the mean of the differences of the average velocities is 0.03m/s, in this study this value is 0.010m/s (see Figure 8, GymAware, squat) but for intensities of 40%, 60% and 80% of 1RM. Banyard et al. (2017) examined the validity of GymAware and PUSH Band 1.0 in the squat by comparing these systems with measurements of a laboratory based testing device consisting of four linear position transducers. They conclude that the accuracy of GymAware is high (no significant differences in ten men's mean velocities at different intensities relative to the 1RM), whereas the accuracy of PUSH Band 1.0 to measure mean velocity is questionable. In a recent study Jovanovic and Jukic (2020) addressed the within-unit reliability and between-units agreement of GymAware and PUSH Band 2.0 in hexagonal barbell deadlift using two PUSH Band 2.0 devices and two GymAware devices. They found that PUSH Band 2.0 devices overestimated mean velocity. Their equations of two regression lines, each determined by comparing one GymAware device with one PUSH 2.0 device are $y = -0.044\text{m/s} + 0.943x$ and $y = 0.045\text{m/s} + 0.85x$ where x is the mean velocity measured by PUSH Band 2.0 and y is the mean velocity measured by GymAware. The study of Lake et al. (2019) addressing bench press exercise suggests that the mean velocity determined by PUSH Band 2.0 may not be fully valid.

A limitation has to be mentioned critically: The study was designed in a way to get a wide range of all possible influencing factors like testing exercises, loads, range of motions, 1RMs, body mass, body height, velocities and so on to cover typical conditions of real training sessions for the use of the measurement systems. Investigating the influence of these factors is beyond the scope of the article. Therefore, we neglected the problem of “nested” data: The measurement data of an athlete may tend to be more alike to each other than to the data of the other athletes e.g. because of the body height or the range of motion of each athlete.

Conclusion

In high-performance sports, it is necessary to measure velocity accurately in order to be able to control intensity. GymAware and Vmaxpro provide valid results determining mean velocity in squat, barbell rowing and deadlift whereas PUSH Band 2.0 seems to be not fully valid.

However athletes and coaches always should be aware of the LoAs of the measurement systems they use in their strength training to control velocity.

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