INSTRUMENT, ANALYSIS, AND COACHING CONSIDERATIONS WITH VELOCITY-BASED TRAINING

by

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Abstract

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The purpose of this thesis was to assess: 1) The validity of commercial instruments to quantify barbell velocity, 2) The influence of an instruction to attain a specific target velocity in comparison to “move as fast as possible” on barbell velocity and subsequent repetition maximum test performance, and 3) The variability in load-velocity profiles and maximum velocity capabilities between athletes, and if the variability in training intensity is dependent on the absolute velocity target. GymAware was found to be valid across the widest range of velocities, followed by Tendo. PUSH was not valid. Participants moved faster when provided with a specific target velocity ($p < 0.001$) with no difference in subsequent repetition maximum test performance ($p = 0.43$). Finally, there was large variability in load-velocity profiles and maximum velocity capabilities between athletes. Faster absolute velocities also yielded greater variability in training intensity ($p < 0.001$).
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Chapter 1

Introduction
1.0.1 Background

Training parameters such as the frequency (repetitions, sets and sessions), intensity (load, ratings of perceived exertion, or tempo), time (work and rest intervals) and type (exercise and modality) are manipulated to elicit specific training adaptations [1–3] in periodized exercise programs. Loads within these programs are typically assigned based on a percentage of the performer’s maximum or sub-maximal strength [4, 5], through direct assessment of the performer’s one repetition maximum (1RM) or the use of repetition maximums (ex. 10RM) [6]. However, because many external factors can influence a performer’s 1RM or 10RM on a daily basis [7–10], the load that corresponds to 80%, for example, may vary from day-to-day.

Although several external factors that may influence daily changes in maximal strength can be controlled, others may be unmanageable for the exercise professional. For this reason, the use of autoregulation, or changing the parameters of an exercise program (ex. repetitions, intensity) based on the current state of the performer may be beneficial for managing cumulative training loads [5]. One proposed method of autoregulating exercise intensities is prioritizing the number of repetitions performed in a given set, which can be effective for increasing maximum strength [5]. For example, if eight repetitions are attained with an 85% load during a session, the next session’s training load may increased by 2.5kg. However, if ten repetitions were attained, the training load may instead increase by 5kg [5]. A second method is to prioritize tempo (i.e. velocity). For example, the training load may be based on the maximum load that can be lifted at a predetermined velocity. Velocity-Based Training (VBT) is a training strategy that utilizes near real-time velocity data to make objective training decisions within and between sessions. An exercise program that has regulated training intensity by prioritizing velocity has been shown to elicit statistically significant strength, vertical jump, and sprint time improvements in U16 and U18 soccer players [11]. However, it is important to note that the cited study did not compare these improvements relative to a group performing traditional resistance training, and thus it cannot yet be stated whether a program that prioritizes movement velocity would necessarily be more effective than a training program prioritizing the load or number of repetitions performed in a set.

Objective feedback regarding a performer’s movement velocity can be used to compare individuals’ load-velocity profile, estimate 1RM performance from sub-maximal loads without lifting to muscular failure or using perceptual measures, predict daily readiness, control fatigue and exertion without any perceptive measures, and/or prescribe exercise loads that accommodate to the performer’s current state of readiness [2]. Velocity data from the lifting phase of a bench press can be used to estimate the %1RM [3, 12–15] ($r=0.84-0.98$) and ratings of perceived exertion (RPE) for an individual based on their load-velocity profile [16]. Additionally, the mean velocity attained with a 1RM load, termed the minimum velocity threshold (MVT) is not statistically different than the mean velocity attained during the final repetition of a repetition maximum (xRM) exertion [17]. Therefore, velocity data could be used to monitor whether an individual is approaching muscular failure during a repetition maximum set. This would allow the exercise professional to objectively determine if the set should be terminated so that muscular failure is not reached.

The utility of this VBT approach is largely dependent on the validity of the equipment being used to monitor velocity. Additionally, it is essential that researchers and exercise professionals use valid
equipment when sharing velocity data between colleagues. Devices such as linear position transducers (LPTs), video cameras, force plates, three-dimensional motion capture systems, and inertial measurement units can be used to measure movement velocity. However, factors such as cost, portability, and time constraints limit the practical application for many of these devices [18]. Additionally, each device will compute the velocity of different objects (e.g., barbell, participant’s center of mass, body segment, etc.) with varying computational methods. Given the relatively small cost and portability of inertial measurement units, they offer a promising solution to quantify velocity data for a variety of activities.

One instrument that has been created to compute movement velocity has been made by PUSH™. This wearable device provides velocity feedback via an inertial measurement unit and mobile application. The device is attached to the forearm with a band and proprietary algorithms are used to compute velocity data of the specific exercise being performed. Therefore, unlike linear position transducers that have been shown to be valid for capturing linear barbell motions [19, 20], the validity of the PUSH™ device is also dependent on the algorithms employed for each exercise. Currently, there is limited evidence documenting the validity of the PUSH™ device and the two most commonly used LPT devices (i.e., GymAware and Tendo), and no studies assessing if the validity of these devices are influenced by the attained movement velocities. Previous research has reported concurrent validity between the mean and peak velocity data \( r = 0.86, \text{SEE} = 0.08 \text{m s}^{-1} \) and \( r = 0.91, \text{SEE} = 0.01 \text{m s}^{-1} \) respectively) collected via a PUSH™ device and the T-Force Linear Position Transducer (the gold standard LPT for this study), as well as high reliability between devices (ICC= 0.907, CI= 0.872-0.933 and 0.944, CI= 0.923-0.959 respectively) during the back squat exercise [18]. It was concluded that the PUSH™ device was valid and reliable in comparison to the T-Force Linear Position Transducer. Another study examined the validity and reliability of PUSH™ with a dumbbell biceps arm curl and a dumbbell shoulder press. High correlation values were reported when compared to a three-dimensional motion capture system \( r=0.801-0.923, p<0.01 \) [21]. However, other studies have concluded that PSH was not valid for quantifying mean and peak velocity data for the back squat [19] or the bench press [22]. Additionally, there are mixed findings as to whether the Tendo device is valid or not, with some studies reporting it to be valid relative to a T-Force Linear Position Transducer [20] for mean velocity data, but not valid relative to a three-dimensional motion capture system for peak velocity data [23].

It is important to note that these studies have not determined if the validity of these devices is influenced by the attained movement velocities. This can be problematic as higher movement velocities may result in greater errors in measurement. A study testing the validity of GymAware and PUSH™ in a back squat with loads ranging from 20-100%1RM relative to a four-LPT lab device and noted that the GymAware was found to be valid, but the PUSH™ was not [19]. However, it is problematic that the devices were analyzed based on the relative loads lifted as some participants may have lifted a relatively heavier load faster than others had lifted a relatively lighter load. Furthermore, the validity of these devices has not yet been explored for the free-weight bench press, a commonly prescribed upper body exercise, in comparison to a 3D motion capture system.

Additionally, the way in which performers are instructed or given velocity feedback may also influence their effort within an exercise set, and thus the short- and long-term training adaptations. If providing objective feedback regarding a performer’s movement velocity, they may move faster and exert a more consistent effort [24, 25]. Additionally, by providing specific velocity targets to attain, goals could
be established. Previous research has suggested that providing challenging goals may be an effective motivation strategy [26–28]. Therefore, by assigning progressively higher target velocities, a performer may move a given load at a greater velocity, which could contribute to superior velocity-specific strength adaptations. However, the instruction and feedback strategies used during VBT programs have not yet been explored.

Training programs that have implemented velocity data have used absolute targets (ex. 1m s\(^{-1}\)) [3]. However, this recommendation has been made with the assumption that a performer’s maximum velocity is not variable between training sessions, and is similar to other performers being tested. However, previous research has noted variability in maximum velocity capabilities between athletes [29]. Therefore, assigning training loads based on absolute velocities may not accommodate the unique abilities of each performer and their potential day-to-day changes in maximum velocity. Therefore, assigning loads based on a *relative* velocity (%V\(_{\text{max}}\)) may be more appropriate. However, this approach has not yet been evaluated in the literature.

The aim of this thesis was to help researchers and exercise professionals better understand the potential implications of implementing an exercise program that uses near real-time velocity data to make objective training decisions. By assessing the validity of commercial velocity-based devices, the effect of velocity-specific instructions and feedback on bench press velocity, and the potential implications of regulating training intensity with absolute and relative velocities, this thesis provides researchers and exercise professionals with insight towards the design and implementation of VBT training programs.

### 1.0.2 Significance

This thesis provides researchers and exercise professionals with data regarding the validity of the three most commonly used commercially available velocity measurement systems (GymAware, Tendo and PUSH\(^{\text{TM}}\)) in comparison to a three-dimensional motion capture system. As there is limited to no data examining the validity of these commercial devices relative to a 3D motion capture system at a spectrum of movement velocities, this thesis provides understanding of their utility during maximum load, maximum speed, and intermediate load/speed training. It also provides data to highlight the potential effect of velocity-specific instructions and feedback on the velocity attained during a bench press. Finally, it provides practitioners with information of how velocity data can be effectively collected and conveyed to performers in a training session.

### 1.0.3 Global Thesis Objectives

Velocity-Based Training utilizes a performer’s movement velocity to make informed decisions during training. Currently, little is known about the validity of commercially available velocity-measuring devices, as well as how the data collected should be interpreted and used in a training setting. To provide researchers and exercise professionals with data pertaining to the implications of utilizing real-time velocity feedback during training, two data collections were conducted to address three main thesis objectives:

1. Assess the concurrent validity of mean and peak velocity data produced by the GymAware, Tendo, and PUSH\(^{\text{TM}}\) in reference to a three-dimensional motion capture system during a free-weight bench
press at mean velocities of: \( \leq 0.40, >0.40- \leq 0.80, >0.80- \leq 1.20, \) and \( >1.20 \text{m s}^{-1} \), and peak velocities of: \( \leq 0.80, >0.80- \leq 1.20, >1.20- \leq 1.60, \) and \( >1.60 \text{m s}^{-1} \).

2. Compare the influence of two velocity-specific instructions (i.e. “move as fast as possible” vs. “attain a target velocity of 1.0\text{m s}^{-1}”) on the maximum mean velocity attained during consecutive bench press sets and subsequent repetition maximum performance.

3. Quantify the variability in load-velocity profiles and maximum velocity capabilities between performers, as well as assess if the variability in intensity (\%1RM, \%V\max) is dependent on the absolute velocity target.

### 1.0.4 Thesis Overview

This thesis involved two data collections to address the three objectives outlined above. Data from the first collection was used to address objectives 1 and 2, while data from a previously collected dataset was used to address objective 3. The first investigation assessed the validity of the GymAware, Tendo, and PUSH\( ^\text{TM} \) devices during a free-weight bench press at the proposed mean and peak velocity ranges. The data for Investigation II was collected concurrently with Investigation I. This second investigation was designed to compare the differences in mean and peak velocity during a free-weight bench press when performers were given two different instructions (i.e. as fast as possible vs. target velocity). The residual effects of each instruction were assessed by comparing the maximum number of repetitions that could be performed at a previously determined load (i.e. 75\% 1RM) following the instruction protocol. Investigation III analyzed previously published data from Frost et al. [30] to assess the implications of using instructions with absolute or relative velocity targets on training intensity.

### 1.0.5 Research Questions and Hypotheses to be Tested

1. **Validity of the Gymaware, Tendo, and PUSH\( ^\text{TM} \) During a Free-Weight Bench Press**
   - **Question:** Are the GymAware, Tendo, and PUSH\( ^\text{TM} \) valid instruments to measure mean barbell velocity in ranges of \( \leq 0.40, >0.40- \leq 0.80, >0.80- \leq 1.20, \) and \( >1.20 \text{m s}^{-1} \) and peak velocity in ranges of \( \leq 0.60, >0.60- \leq 1.20, >1.20- \leq 1.80, \) and \( >1.80 \text{m s}^{-1} \)?
   - **Hypothesis:** The GymAware and Tendo devices will be valid relative to the motion capture system at all tested velocity ranges, however the PUSH\( ^\text{TM} \) devices will not be valid at the tested velocity ranges due to previous findings from the published literature.

2. **Does the Instruction to Move “As Fast As Possible” Maximize Voluntary Movement Velocity? - Coaching Considerations with Velocity Feedback**
   - **Question A:** Does an instruction to attain a target velocity of 1.0\text{m s}^{-1} with a 45\%1RM load result in faster movement velocities in comparison to an instruction to “move as fast as possible”?
   - **Hypothesis A:** An instruction to attain a mean velocity of 1.0\text{m s}^{-1} will result in faster movement velocities with 45\%1RM in comparison to an instruction to “move as fast as possible” during a free-weight bench press.
• Question B: Does an instruction to attain a target velocity of 1.0 m s\(^{-1}\) with a 45%1RM load result in greater fatigue during a subsequent repetition maximum test (i.e. less repetitions performed) in comparison to an instruction to “move as fast as possible”?

• Hypothesis B: An instruction to attain a mean velocity of 1.0 m s\(^{-1}\) will result in fewer repetitions performed during a repetition maximum test in comparison to an instruction to move as fast as possible.

3. Velocity-Based Training: Exploring the Potential Implications of Training with Absolute versus Relative Velocities

• Question A: How variable is the load-velocity profile and maximum velocity capabilities between performers?

• Hypothesis A: There will be large variability in performers’ load-velocity profiles and their maximum velocity capabilities.

• Question B: Is the variation observed in the estimated relative loads and velocities dependent on the absolute velocity?

• Hypothesis B: Faster absolute velocities during training will yield greater between-subject variation in %1RM and %Vmax.
Chapter 2

Review of Literature
2.0.1 Velocity Specificity for Speed and Power Development

The development of speed and power are desirable adaptations for a variety of sports [31–33]. For athletes with limited training experience and low levels of muscular strength, the literature has suggested that general strength training alone may be enough to improve their speed and power production [34–36]. However, as athletes gain more training experience and become stronger, they require greater specificity to attain these targeted adaptations [37]. Various studies with isokinetic devices have demonstrated that strength adaptations appear to be specific to the actual training velocity [38–45], suggesting that faster movement velocities should be prioritized during training for the development of speed and power. These velocity-specific adaptations are also seen while performing multi-joint movements, such as jump squats, while training with isoinertial loads [46]. For example, Delecluse et al. examined sprint performance changes in 72 male students following training programs that prioritized either high-velocity or high-resistance for 9 weeks. It was found that the high-velocity training group improved their 100m sprint time ($p < 0.05$) and initial sprint acceleration ($p < 0.05$), whereas the high-resistance training group did not [47]. In addition to the peer-reviewed literature, various texts have also cited the importance of prioritizing faster movement velocities for the development of speed and power [48–50], with some citing velocity ranges to attain these adaptations [51].

There has also been evidence to suggest that the actual movement velocity is not responsible for developing velocity-specific adaptations. A frequently-cited paper by Behm and Sale contradicts the abovementioned velocity-specific findings and states that the intent to move as fast as possible is responsible for velocity-specific training adaptations [52]. It is important to note that the applicability of the authors’ findings may be limited given that a within-subjects design was used whereby the dorsiflexors of one limb were trained isometrically and the dorsiflexors of the other limb were trained isokinetically. More recent work has shown that the contralateral limb can benefit from unilateral strength training [53–56]. It is therefore possible that the adaptations gained in one limb were “crossing over” into the other, clouding the velocity-specific adaptations. Another study that supports Behm and Sale’s findings compared high and low velocity training and its transfer to seated netball throwing velocity [57]. The authors suggested that velocity-specific training may not improve throwing velocity any more than low-velocity strength training. However, an untrained female population was used, and therefore these data may not reflect the adaptations that would be seen amongst a trained, more experienced cohort. Additionally, both groups performed 20 netball tosses following each set of smith machine bench presses during the training program. Therefore, the similar improvements in a netball toss with both high- and low-velocity training may have also been due to increased familiarity with the testing movement.

Lending further support for the notion of velocity-specific training, several studies have shown a velocity-specific training response even when the intention to move as fast as possible was instructed between both high- and low-velocity training groups [38–42, 44]. For example, an investigation by Bell et al. [44] trained eighteen oarsmen four times per week for five weeks. Participants were placed into a high- or low-velocity training protocol. The resistance used was adjusted as necessary to ensure that the involved joints maintained an angular velocity of about 1.1 rad s$^{-1}$ in the low-velocity group and 3.1 rad s$^{-1}$ in the high-velocity group. In both groups, participants were instructed to impart maximum effort throughout the training protocols. They found that both groups increased their peak knee torque capacity at or near the actual training velocity. Although these velocity-specific findings were noted
while training at higher velocities, the intention to move as fast as possible is still important. For example, González-Badillo et al. [58] compared velocity-prioritized training programs that instructed athletes to perform a bench press in two different ways: 1) each repetition was performed at 100% of the highest movement velocity that participants could attain with a given load (MaxV group); and 2) each repetition was performed at 50% of the fastest movement velocity that participants could attain with a given load (HalfV group). After six weeks of training, the MaxV group had a greater increase in their 1RM bench press strength, as well as the average velocity they could attain when bench pressing heavy and light loads in comparison to the HalfV group. The same research group conducted a similar study with the back squat [59] and found that the MaxV group improved their countermovement jump height significantly more than the HalfV group. Since the HalfV group did not attempt to lift as fast as possible, it is likely that both the intent to move as fast as possible and the actual movement velocity contribute to the development of velocity-specific adaptations. Therefore, advanced trainees may stand to benefit from both prioritizing faster movement velocities during training while also imparting a maximum effort. There are various mechanisms that may be responsible for these velocity-specific training adaptations.

Learning Effects and Changes in Movement Kinematics

A potential mechanism that might explain these velocity-specific adaptations are the kinematic changes that may occur following training. For example, factors such as the coordination of an arm swing [60, 61], the use of a countermovement [61] and the angular displacement of the knees and hips [62] can all influence vertical jump height. In a study by Arabatzi et al. [63], participants performed the Olympic lifts (and their derivatives) three days per week for eight weeks. Following this training period, participants' angular displacement at the hip and knee joint was greater during a vertical jump relative to baseline and to that of a plyometric training protocol and a control group, resulting in increased vertical jump performance. Furthermore, kinematic changes can be influenced by the instructions utilized in a training program. Instructions that draw a performer’s attention to the outcomes of their movement (external focus) have also brought about greater displacements of the center of mass and vertical jump height [64]. When instructing athletes to focus on their movement outcomes (ex. move the barbell as fast as possible), this external focus of attention may also be contributing to changes in coordination that are responsible for velocity-specific training adaptations. Therefore, changes in movement patterns, both due to the exercises performed in the training program and the instructions used, may bring about velocity-specific training responses.

Although kinetic, and the resulting kinematic, changes may potentially be responsible for velocity-specific training responses, there is limited data that analyzes the kinematics of free-weight exercises, such as a bench press, following a high-velocity training program when athletes lift with the intent to move as fast as possible. One such study by Almasbakk and Hoff [65] examined the influence of four training interventions on velocity-specific training adaptations in untrained females: 1) a bench-press training group that performed all repetitions with a wooden stick; 2) a training group utilizing heavy loads in a bench press (80-85% of their maximum performance); 3) an alternative training group that performed shoulder lateral flexion and elbow extension exercises to impose similar muscular demands as a bench press (with 80-85% of their maximum performance); and 4) a control group that did not train. All participants were instructed to lift as fast as possible for each repetition. Three sets of seven repetitions were performed each training session. Training loads for the heavy bench press group and the
alternative group were increased if more than seven repetitions could be performed during the third set. Following six weeks of training (three times per week), both bench press groups significantly increased the mean velocity of their bench press at four absolute loads relative to their baseline, however there were no differences between these two groups. Additionally, while the high load group showed a significantly greater increase in their 1RM bench press, no differences were noted in the peak rate of force development (RFD) achieved at each load in comparison to the light load group. The alternative training group and control group saw no changes in bench press performance. This data suggests that early velocity-specific adaptations might be attributed to changes in participants’ coordination patterns when performing a bench press at a fast velocity. However, the results from this study [65] are limited to an untrained female population and future research with more experienced athletes should be performed before extrapolating these findings to a well-trained population. It is important for future research to establish whether the instructions used during high-velocity training change the kinematics of free-weight exercises, such as the bench press, in experienced athletes, and determine the kinematic changes following a high-velocity training program. With the limited data present in the literature, other assumptions have been made on various central and peripheral mechanisms that may also be responsible for changes in high-velocity performance.

Changes in Muscle Activation

By both intending to move as fast as possible and achieving fast movement velocities, activation of the “agonist” muscles may differ in comparison to lower velocity training. For example, Tillin and Folland found that when performing isometric knee extensor contractions, the group that performed contractions while instructed to extend “fast and hard” displayed an increased activation of the knee extensor muscles (rectus femoris, vastus lateralis, and vastus medialis) during the first 50ms of contraction relative to the group performing sustained isometric contractions (cued to maintain 75% of their maximum voluntary contraction force) [66]. Although this was not a dynamic model, it suggests that neural activity and force development during the onset of the contraction may be developed when intending to move as fast as possible.

These findings are consistent when examining dynamic movements. For example, a study by Cutsem et al. [67] found that following twelve weeks of high-velocity training, EMG activity of the ankle dorsi flexor muscles occurred sooner to the start of the movement, the maximum firing frequency of motor units increased, and brief interspike intervals (doublets) in the EMG burst of ballistic contractions emerged \((p<0.001)\). However, this study used an isokinetic device for training and testing, and adaptations may not necessarily be similar to multi-joint movements due to differences in coordination [68]. McBride et al. [46] analyzed the effect of heavy- vs. light-load jump squats on muscle activity during jump squats with 30%, 55%, and 80% 1RM. Following 8 weeks of training, the group using the lighter load, and thus faster movement velocities, demonstrated a greater increase in EMG activity in the knee extensors when jumping with 30% of their baseline 1RM than the higher-load/lower-velocity group. This finding was consistent with that of Hakkinen and Komi [37] and Mero and Komi [69]. Additionally, there may be reduced coactivation of “antagonist” muscles following high-velocity training. Activation of muscles opposing the direction of movement (ex. hip flexor muscles activated during the hip extension phase of a vertical jump) can reduce the net force output and impair agonist muscle activity via reciprocal inhibition [70]. Pousson et al. [71] reported that following seven weeks of elbow flexion training, a
high velocity training group showed significantly decreased coactivation of antagonist muscles (triceps brachii) at higher velocities \( (p < 0.05) \).

The shortening velocity of the muscles has also been suggested to increase in response to training programs that emphasize faster movement velocities. For example, following eight weeks of maximum effort stretch-shortening cycle exercises, single-fiber contraction velocity was enhanced in type I, IIa and IIa/IIx fibers, leading to increases in vertical jump performance [72]. A similar finding was noted by Duchateau and Hainau [73] who examined the influence of isometric and dynamic strength training programs on maximum shortening velocity of the adductor pollicis muscle in the nondominant hand during an electrically simulated muscular contraction. They found that maximum shortening velocity was only increased after the dynamic training \( (p < 0.05) \). More importantly, this was found during involuntary contractions, further suggesting that some other peripheral mechanisms may be responsible for increases in muscle fiber contraction velocity. Therefore, prioritizing faster movement velocities during training will likely increase the single-fiber contraction velocity, which may translate to improved performance in multi-joint movements like a vertical jump. This increase in shortening velocity may be explained by characteristics of the muscle fiber itself, or in the fascicle lengths of a muscle.

Prioritizing faster movement velocities may also be beneficial as it would also not allow movement velocity during exercise to become too slow. Pareja-Blanco et al. [74] compared load-matched training programs that used two different methods to terminate an exercise set: 20% loss in velocity over the set (VL20) vs. a 40% loss in velocity over the set (VL40). Their data showed a significant reduction of myosin heavy chain-IIIX expression (the myosin isoform that contracts the fastest) in the VL40 group with no decrease in the VL20 group. This may explain why the VL20 group displayed greater improvements in vertical jumping and sprinting ability following training, and similar increases in 1RM back squat strength despite performing 40% fewer repetitions and 36% less mechanical work in the 8-week training intervention. Although the current research suggests that training at faster movement velocities may not necessarily influence muscle fiber type, it seems that training at these velocities may reduce the likelihood of developing muscle fiber characteristics with a slower shortening-velocity.

Previous research has also demonstrated that the number of sarcomeres arranged in series, and thus the fascicle length, was a major determinant of the velocity potential of a muscle [75]. Another investigation by Blazevich et al. [76] supports this finding. Following four weeks of squat training, forward hack squat training, or sprint/jump training in eight female and fifteen male athletes, only the sprint/jump group had a significant increase in vastus lateralis fascicle length. Alegre et al. [77] also reported an increase in fascicle length of the vastus lateralis (10.3%) following 13 weeks of high velocity squat training. Therefore, it is possible that following a period of high velocity training, an increase in muscle fascicle length may increase the maximum velocity potential of a muscle. This is noteworthy given that the muscle fascicle lengths of the vastus lateralis and gastrocnemius medialis and lateralis has been significantly correlated with 100m time in sprinters \( (r = -0.40 \text{ to } -0.57, \ p < 0.05) \) [78]. By prioritizing faster movement velocities in training, it appears that changes in the fascicle length of the muscle may increase the shortening-velocity potential of the muscle.
Summary of Mechanisms of Velocity-Specific Adaptations

The current literature strongly suggests that, especially for experienced athletes, prioritizing faster movement velocities during training is important for eliciting velocity-specific training adaptations, such as increases in vertical jump height. By prioritizing faster movement velocities and instructing athletes to impart a maximum effort during training, their attentional focus may shift and result in kinetic and kinematic changes that improve velocity-specific training adaptations. However, research examining the kinematic changes with instructions focusing on eliciting an external focus of attention while following high-velocity training programs is limited to a single study with untrained females. Therefore, future research should be performed to examine kinematic changes during free-weight exercises with external coaching cues and high-velocity training programs. In addition to the kinematics of exercise, it has also been suggested that changes in muscle activation (agonist and antagonist muscle activity) may be responsible for velocity-specific adaptations. There are also characteristics of the muscle fibers that may contribute to increasing the shortening-velocity potential of muscle, such as the composition of muscle fiber types and the fascicle length.

2.0.2 Traditional Training Versus Autoregulation

High-velocity training can provide substantial advantages for certain objectives; however, researchers and exercise professionals must design their program to maximize their athletes’ performance. The periodization of training programs is the planned manipulation of exercise variables, such as the frequency, intensity, time and type of exposure, and is commonly used to achieve specific short- and long-term training adaptations [79, 80]. For example, faster movement velocities may be planned in training to improve vertical jump performance, increase muscle fascicle length, increase agonist muscle activation, or produce greater peak joint torques during fast movement velocities. Periodized training programs are further divided into macrocycles, mesocycles, and microcycles [79]. Macrocycles are longer-term plans (around one year) which are then further divided into mesocycles and microcycles. Mesocycles are shorter-term plans that are more specific than the overarching goal of the macrocycle (ex. strength phase, speed phase) and are divided into microcycles. These microcycles are the individual training sessions or weeks that will work towards the goal of the mesocycle (ex. high-load low-velocity sessions, low-load high-velocity sessions). There are numerous ways to plan training programs, with some examples being: linear periodization, non-linear periodization, undulating periodization, block periodization, and concurrent periodization. For additional information regarding these different periodization methods, please refer to [79, 81]. Within these different methods of periodization typically exists a general commonality: using a percentage of one’s maximum strength (i.e. percent of a one repetition maximum, or %1RM) to determine training intensity.

Training intensity is typically regarded as one of the most important variables to manipulate [82]. The training intensity will determine the training loads to be utilized, as well as the effort put forward by the athlete to lift those loads. An athletes maximum strength for a given exercise is usually determined with either a direct test of a 1RM or via an estimation from a RM test [6]. Once one’s maximum strength is established, training intensity can be manipulated by selecting appropriate loads based on a percentage of 1RM. Traditional training programs have relied upon this method of assigning training loads within microcycles and mesocycles. For high-velocity programs, a lower relative load would be
selected to maximize movement velocity.

Fundamentals of Percentage-Load Based Training

There are several approaches used to design exercise programs; however, the most common is assigning a %1RM that will help attain specific training adaptations. For example, speed and power are important for athletes in a variety of sports [33]. Therefore, much attention has been given in the literature to develop these characteristics. Aside from the frequency and type of exercise modalities used, there is a wealth of data pertaining to the exercise intensities that should be used in a training program. These studies have cited that lighter relative loads (i.e. < 50% 1RM) result in the highest maximum power, on average, for a group of athletes [46, 83–85]. In addition to speed and power, maximum strength may also be desirable adaptations for athletes. Similar work has concluded that heavier relative loads (i.e. > 85%1RM) are best for developing this adaptation [86, 87]. Due to the ease of determining a 1RM and the dominance of studies suggesting %1RMs to use for each adaptation, a percentage of one’s maximum strength is usually prescribed to elicit both strength and power adaptations.

Although assigning a %1RM to attain specific training adaptations may be convenient, it is does not accommodate to fluctuations in maximum strength. Previous studies have highlighted that participants can be “high” or “low” responders to training interventions [88], and therefore will progress at different rates. Additionally, there is other data to suggest that the rate of adaptation [89] and recovery [90] from training is individualized and dependent on current strength training experience [91]. Furthermore, there are other factors that might impair maximum strength on any given day (ex. fatigue [7], psychological stress [8], hydration status [9], and supplementation [10]). By prescribing future training loads based on a %1RM from a single strength test, it is possible that an unintended loading parameter could be used during training. It is therefore advisable to create strength training programs that consider these factors.

Autoregulation During Periodized Training Protocols

To address fluctuations in daily strength from fatigue [7], psychological stress [8], hydration status [9], and supplementation [10], several researchers have proposed that training loads should be regulated based on the current state of the athlete. Although this could be done by performing a maximum strength test every workout, it may be impractical and increase the risk of injury [3, 92]. The goal of autoregulation is to prescribe training loads based on the current state of the athlete, without the need to perform consistent maximum strength tests. This would ensure that performers are training at the intended level of intensity while also taking into consideration any fluctuations in maximum strength. There have been several strategies reported in the literature to autoregulate training intensity, such as using the number of repetitions performed, the rating of perceived exertion, and a velocity-based approach.

The earliest study conducted that examined the potential benefits of regulating training based on the current state of the performer was DeLorme [93]. A resistance training protocol was used to rehabilitate soldiers with femoral fractures whereby 2 sets of 10 repetitions were performed with a given load, and then the third set was taken until muscular failure. Depending on the number of repetitions performed in the third set, the weight was adjusted the following session. This method of rehabilitation was found
to be superior for re-establishing muscle strength and size relative to other less-strenuous, conservative approaches. In 1979, Knight [94] built upon this approach, but used the number of repetitions performed in the third set to determine the load for a fourth set. This fourth set was also taken to muscular failure, and the number of repetitions performed determined the training loads for the first three sets of the following workout. Knight also created an additional 6-repetition protocol that can be used in training sessions to complement the 10-repetition protocol created by DeLorme. Finally, Verkhoshansky and Siff [49] theorized an additional 3-repetition protocol that could be used in addition to the existing 6- and 10-repetition protocol.

Until 2010 this autoregulatory approach to progressing resistance training programs had not been tested with experienced athletes. Mann et al. [5] conducted an experiment comparing an autoregulating-progressive resistance exercise (APRE) protocol, similar to that outlined by Verkhoshansky and Siff [49], to a traditional linear periodization protocol with 23 Division I collegiate football players during their preseason. The APRE was implemented for the squat and bench press exercise over six weeks, with the three different protocols used, each consisting of four sets: 10RM; 6RM; and 3RM protocol. The first two sets performed were considered warm-up sets, and used 50% and 75% of the estimated load for the RM protocol. On set three, participants performed as many repetitions as they could with 100% of the anticipated RM protocol. On set four, the load was adjusted based on the number of completed repetitions during set 3 based on a pre-set criterion. For example, if during the 6RM protocol an athlete completed three repetitions, the 6RM load would be reduced by 0-5lbs for set four. Then, depending on the number of repetitions performed with the load during set four the training load was adjusted accordingly for the next training session. Therefore, all progression or regression of exercise intensity was dependent on the repetitions performed by the athlete. The traditional training group started their training regime with sets of 8 with 70% of their 1RM and worked up to a 5RM by increasing their training intensity by a pre-determined percentage each week. The authors found that the APRE group increased their 1RM bench press, 1RM squat, and number of repetitions performed with 225lbs in a bench press significantly more than the traditional training group (p < 0.05). These findings highlight the potential benefit of autoregulating the progression of training intensity based on the number of repetitions performed when the aim is a strength-specific adaptation.

Another approach that has been used to regulate the training intensity involves the Rating of Perceived Exertion (RPE). With this method, each performer is asked to provide an RPE following each set so the training load can be adjusted to suit the target RPE of the session. One potential advantage of this method over the repetition-based approach is that athletes can avoid training to failure, which is not always the aim of strength-oriented programs [95]. Although introduced to gauge a performers perceived exertion during aerobic-style exercise, Zourdos et al. [96] adopted a modified RPE scale, originally introduced in “The Reactive Training Systems Manual” [97], that could be used for resistance training by monitoring the perceived number of repetitions-in-reserve (RPE-RIR) (i.e. number of repetitions until muscular failure). For example, a reported RPE-RIR of 10 would correspond to a maximum effort exertion in which no additional repetitions or load could be added during that set. An RPE-RIR of 9.5 would suggest that no additional repetitions could be performed, however some load could be added without reaching muscular failure. An RPE-RIR of 9 would suggest that the athlete felt they could have performed one more repetition with that given load. This scale ranges from 1-10 in increments of
0.5. Utilizing an RPE-RIR scale may be more appropriate for resistance training in comparison to RPE based on solely perceived exertion [98]. Zourdos et al. [96] found that RPE-RIR scores were significantly correlated to the mean concentric velocity of a back squat at all tested %1RM in both elite ($r = -0.88$) and novice ($r = -0.77$) squatters. Therefore, training intensities could be prescribed via an RPE-RIR and used to accommodate to changes in maximum strength over time.

Although the RPE-RIR method of autoregulation has some advantages over the repetition-based method of autoregulating training, it also has limitations. Firstly, it appears that novice trainees are not as accurate at gauging repetitions-in-reserve in comparison to their experienced counterparts, and are less accurate in predicting %1RM [96]. Furthermore, this method may not be appropriate when training sets are performed with lighter %1RMs, and thus higher velocities, since they are not close to volitional failure [99].

It is important to also consider that programs utilizing a %1RM approach to prescribing training loads can be adjusted based on the daily readiness of performers. This can be done subjectively by qualitatively assessing their movement velocity or objectively if they have reached muscular failure during a set. However, this must be done retroactively rather than prospectively, and it would have to be based on the exercise professional’s perception of the performer. Therefore, it appears that the regulation of training intensity based on the performer’s state of readiness, whether this be with actual repetitions performed or by repetitions in reserve, is a superior approach for strength-specific training. As noted above, several limitations exist if using this approach with lighter relative loads or faster movement velocities.

**Autoregulation with Velocity-Based Training**

A relatively new approach to autoregulation is the Velocity-Based Training (VBT) approach. Velocity data is computed in near real-time for the researcher or exercise professional to objectively monitor a performer and regulate training based on their current state.

Monitoring the velocity during the lifting phase of an exercise can be used to estimate 1RM and %1RM if performed as fast as possible. Gonzalez-Badillo et al. [3] analyzed the relationship between the mean “propulsive” velocity (i.e. phase when acceleration of barbell is greater than 0m s$^{-2}$) (MPV) and %1RM. In their investigation, 120 participants performed a 1RM test for the bench press. All repetitions were performed with a 1.5 second pause between the descending and ascending phases. All participants started with a 20kg load and progressed by 10kg increments until the MPV was less than 0.5m s$^{-1}$. The load was then adjusted with 1kg to 5kg increments so the 1RM could be determined with greater precision. Once the 1RM was established, participants performed three attempts with a light load (MPV > 1.0m s$^{-1}$), two attempts with a medium load ($0.65 m s^{-1} \leq MPV \leq 1.00m s^{-1}$, and one attempt with a heavy load (MPV < 0.65m s$^{-1}$). After fitting a second-order polynomial curve to the %1RM and MPV data, a strong relationship between these variables was observed ($R^2 = 0.981$, SEE= 3.56%1RM). The authors also reported an equation that could be used to estimate %1RM with similar accuracy using the mean velocity (MV) as well ($R^2=0.979$, SEE= 3.77%1RM). In a similar investigation analyzing the back squat, it was determined that the %1RM could be estimated with MPV ($R^2= 0.954$, $SEE= 3.55%1RM$).
In addition to the second-order polynomial models used to estimate \%1RM from velocity (to better represent the force-velocity curve outlined by A.V Hill [102]), other investigations have used simpler linear models instead. For example, Jidovsteff et al. [13] used mean velocity data of 112 participants retrospectively from three different studies to create a linear regression model that can predict maximum strength based on the estimated load at 0m s\(^{-1}\) (LD0) (i.e. maximum isometric strength). Participant-specific linear regression equations were built using the highest mean concentric velocities from a bench press with 3 or 4 loads (i.e. 35, 50, 70, and 90\% 1RM in study 1, 40, 60, and 80\% 1RM in study 2, and 30, 50, 70, and 95\% 1RM in study 3). After creating a regression equation for each participant based on the mean concentric velocity attained at each absolute load, a velocity of 0m s\(^{-1}\) was input into the equation to estimate the maximum isometric strength of the participant. Participants’ tested 1RM was then compared to the maximum isometric strength estimate. The correlation between participants’ 1RM and maximum isometric strength was 0.98 (SEE= 7\% 1RM), suggesting that movement velocity can be used to estimate maximum strength performance.

Another study utilizing a linear model to estimate \%1RM from MV also showed similarly strong associations between the relative load and velocity \((r=0.93, p<0.001)\), but a large bias between the actual and estimated 1RM (Bias= 5.4 ± 5.7kg, \(p<0.001, ES= 1.37\)) [12]. Banyard et al. [103] also conducted a study to assess the MV attained during a free-weight back squat in strength-trained participants during three different testing sessions. Each repetition was performed with no pause between the descending and ascending phase (i.e. utilizing the stretch shortening cycle). The relative loads used to build the \%1RM-MV model were 20, 40, 60, 80, and 90\%1RM. It was concluded that a linear model produced significantly different 1RM estimates than the actual 1RM attained by the participants \((p<0.05, ES= 0.71-1.04)\). Additionally, the variation in the actual 1RM between the three testing sessions ranged from -5.6-4.8\%, but the estimated 1RM ranged from -5.5-27.8\%. In Banyard et al.’s investigation, the linear association between \%1RM and MV was also similar to that of other studies \((r=0.93, SEE= 10.6kg, CV= 7.4\%\). The discrepancies noted in the studies by Gonzalez-Badillo et al. [3] and Sanchez-Medina et al. [100, 101] and those of Bosquet et al. [12] and Banyard et al. [103] may be due to the second-order polynomial models used in the former studies and the linear models used in the latter studies. Additionally, the use of lighter relative loads in the prediction equation and only two sets above 80-90\%1RM may have decreased the accuracy of the generated models [99], similar to how lighter relative loads during a repetition maximum test are less accurate at estimating 1RM [104]. Therefore, more loads above 80\%1RM should be used to generate models to accurately estimate 1RM. It has been suggested that: 1) at least 4-6 loads between 30-85\% 1RM, 2) there should be a minimum difference between the fastest and slowest exercise velocity of 0.50m s\(^{-1}\), and 3) every repetition should be performed repetition performed as fast as possible when building these models [2, 103].

Mean velocity and RPE-based methods have shown to estimate relative load with similar accuracy [14, 96, 99, 105]. However, there are distinct advantages of using a VBT approach to autoregulate training versus RPE-RIR or RPE when training for high velocity-specific adaptations. For instance, novice trainees are less reliable with reporting RPE than more experienced trainees. Therefore, assessing RPE-RIR with a less experienced athlete may produce larger errors in load prescription. Additionally,
RPE-RIR is much less effective when utilizing lighter training loads that are not close to volitional failure as there may still be many repetitions in reserve, making it difficult for athletes to gauge accurately [99]. Since lighter relative loads are utilized when prioritizing faster movement velocities during training, a VBT approach allows for more accurate autoregulation of training even when light relative loads are being used.

There is currently limited research analyzing the effectiveness of training programs that are regulated by training velocity. González-Badillo et al. [11] evaluated the efficacy of a VBT training program with young soccer players by having a U16 and U18 team from the same club perform two resistance training sessions per week. The U21 team from the same club only performed typical soccer training. The load that the players could lift with a mean velocity of 1.0m s$^{-1}$, countermovement jump performance, and 20m sprint performance were compared between- and within-groups following the intervention. In total, 44 players were included in the analyses following 26 weeks of training. Training loads during the resistance training program for the U16 and U21 were assigned based on the load that they could squat at 1.0m s$^{-1}$ (e.g., 80%V1-load). In addition to back squats, the training program also consisted of loaded and unloaded counter-movement jumps, sled towing, triple jumps, change of direction sprints, and linear sprinting. The squats were performed twice per week and the other exercises were performed once per week. In the 7th and 15th week of the study, the loads that could be lifted at 1.0m s$^{-1}$ for the squat were adjusted to better reflect their current strength levels. In the back squat test, the maximum load that could be lifted at 1.0m s$^{-1}$ was determined. There was a significant difference between the U16 and U18 group ($p=0.001$, ES= 1.13) and the U16 and U21 group ($p=0.001$, ES=1.49), but not the U18 and U21 group ($p=0.67$, ES=0.24). For the countermovement jump test, significant differences were found between the U16 vs U21 group ($p=0.01$, ES= 0.77), but not between any other groups. Significant differences were also found for 20m sprint times with the U16 and U18 groups ($p<0.05$), whereas the changes in sprinting ability for the U21 group was unclear. The authors concluded that this VBT program could improve strength and speed in young soccer players, and that the physical abilities of the U16 and U18 players were on par with or overcame the U21 players that did not perform the training protocol. Although this study used a VBT protocol, the authors highlighted that the investigation was not a true experimental design, and it is therefore difficult to obtain a causal relationship between the training program used. Therefore, it cannot be said whether this type of training program would have been more effective than any other form of resistance training (i.e., percentage load-based protocols). Additionally, the authors reported that the players’ maturation and age may have played a role in the magnitude of the performance increases.

Another study that prioritized the mean power production, which is related to movement velocity, during the training of professional soccer players in the back squat exercise also demonstrated increased performance in repetition maximum tests ($p<0.001$, ES= 1.93), relative power production ($p<0.001$, ES= 1.00), absolute power production ($p<0.001$, ES= 0.88), peak force production ($p<0.001$, ES=0.50), and velocity ($p<0.001$, ES=1.00) with a 65% 1RM load [106]. In this investigation, participants trained twice per week for ten weeks. Participants lifted a 65% 1RM load that was established at baseline, and performed 4 sets of 10-25 repetitions per set. The number of repetitions per set was determined by the power produced during each rep; once the power output fell below the maximum power output measured during their baseline test for two consecutive repetitions, the set was terminated. Although there is not
yet enough strong evidence to support the use of VBT in training due to the nature of the study designs, the successes of autoregulating training by repetitions or RPE-RIR and the positive results from these two studies suggest that it would likely be an effective training intervention. However, future research would need to compare the resulting adaptations from a VBT protocol to that of a traditional strength training protocol to evaluate the utility of this training approach.

In addition to autoregulating training, velocity data can also be used to monitor effort and metabolic byproducts associated with fatigue. Sanchez-Medina and Gonzalez-Badillo [107] recruited 18 professional firefighters or firefighter candidates with resistance training experience ranging from 3-5+ years. During a period of 8 weeks, 21 testing sessions were performed (one 1RM and load-velocity profile test, repetition maximum tests with 4, 6, 8, 10, and 12RM, and 15 “REP” tests that had athletes perform three sets with a load at or near a repetition maximum - for example, 3 sets x 6 repetitions with a 12RM load, and 3 sets of 12 repetitions with a 12RM load) with half the participants performing back squats and the other half performing bench presses. Fatigue was quantified by computing the decrease in MPV relative to the fastest movement velocity recorded within the set, the percent change in MPV pre- and post-exercise attained with a load that participants could lift at 1.0m s\(^{-1}\) during the propulsive phase, and by examining the percent change in countermovement jump height pre- and post-testing. Lactate and ammonia concentrations from blood samples drawn from the fingertip before exercise and immediately following each REP were also observed. The authors found that as the number of repetitions in the “REP” tests approached maximum levels (ex. 3 sets x 12 repetitions with a 12RM load), the relative MPV loss was significantly greater over the three sets. Additionally, a high correlation (r=0.91 for squat, r= 0.97 for bench press) was found between relative loss of MPV over three sets and loss of MPV pre-post exercise with the load that could be lifted at 1.0m s\(^{-1}\). Furthermore, a high correlation between MPV loss over the three sets and post exercise peak lactate was found for both the squat and the bench press (r=0.97, p< 0.001 and r= 0.95, p< 0.001, respectively). Lactate appeared to follow a linear increase with greater velocity loss, whereas the response of ammonia was curvilinear, suggesting that there could be an accelerated purine nucleotide degradation, which would require longer recovery times. This data suggests that velocity loss during exercise may reasonably estimate the metabolic stress and associated neuromuscular fatigue incurred during an exercise set.

Another use of velocity data may be to estimate volitional failure during exercise. Previous research by Izquierdo et al. has demonstrated that the mean velocity attained during a 1RM, termed the minimum velocity threshold (MVT) is not statistically different than the mean velocity attained during the final repetition of a repetition maximum test [17]. In this investigation, participants performed repetitions until failure with 60, 65, 70, and 75% of their 1RM and found that the mean velocity of the last repetition in each set was not different between these loads and 100% 1RM. It is important to note, however, that the MVT of different exercises are not similar, and the MVT of the same exercise has differed between investigations [17, 99], suggesting there is no universal MVT between people and exercises. This discrepancy in MVT between investigations may be due to the differences in training experience of the populations tested. Therefore, velocity data may be used to monitor fatigue and estimate failure to assist in regulating training, however each exercise and population subset will likely correspond to a different MVT.
Jovanovic and Flanagan [2] built upon this knowledge to build an exertion-velocity profile that can estimate the number of repetitions in reserve based on the mean velocity of the lifting phase of an exercise. They analyzed the mean velocity of back squat repetitions from the previously mentioned study by Izquierdo et al. [17] for each repetition in reserve. They demonstrated that across all loads that there was a small standard deviation and coefficient of variation of the MPV when a certain number of repetitions were left in reserve (ex. 6 repetitions in reserve corresponded to an MPV of approximately $0.47 \pm 0.01 \text{m s}^{-1}$, CoV= 3%). This suggests that movement velocities can be monitored during an exercise set to not only determine the general fatigue of the athlete or whether they are close to muscular failure, but they can also be used to determine the number of repetitions-in-reserve until muscular failure. By using velocity data to determine an athlete’s load-velocity profile, their MVT, and the number of repetitions-in-reserve during a set, the exercise professional or researcher can objectively monitor exercise intensity and regulate training accordingly.

Velocity data can also be used to provide augmented feedback for athletes. In a randomized cross-over study by Randell et al. [24], twenty semi-professional rugby players were split into a feedback or non-feedback group. Participants performed jump squats, controlled to 90° of knee flexion, with a 40kg load, and were instructed to perform each repetition as “explosively as possible”. Athletes in the feedback group were provided feedback of their peak velocity following each repetition, whereas athletes in the non-feedback group performed the same protocol without receiving any feedback. The testing sessions were replicated an additional two times before the two groups crossed-over (i.e. feedback group became non-feedback group). It was found that when feedback was provided, there was an increase in jump squat velocity (5.3%) and a plateau/decrease in jump squat velocity after the feedback was withdrawn (-1.2%). When adjusted for the cross-over effect, providing feedback increased the average peak velocity by 2.1% ($p= 0.018$; CI= 0.7-3.5%). This change was also described as practically beneficial with 78% certainty (likely benefit). Using the same dataset, Randell et al. [25] reported that augmented feedback also resulted in lower variations in movement velocity. This suggests that with velocity feedback, athletes can also potentially achieve greater consistency in their improved performance. Therefore, more research is needed to determine if athletes’ performance is more consistent when given feedback of their movement velocity. Improved consistency of performance may allow athletes to attain superior training adaptations due to an increased number of repetitions being performed at a faster movement velocity.

Summary of Traditional Training Versus Autoregulation

It is important to plan training programs to elicit desirable training adaptations at specific times while managing fatigue. Training intensity is commonly prescribed by determining the maximum strength of the performer and then prescribing a %1RM. However, this method of prescribing training intensity can be problematic as maximum strength can fluctuate daily, and consistently testing maximum strength may not be practical. It is therefore suggested that training intensity should be regulated based on the current state of the performer. Although the intensity of training can be regulated by the number of repetitions performed or the RPE-RIR, the utilization of a VBT approach has many distinct advantages when faster movement velocities are the priority of training. Furthermore, monitoring exercise velocity can also be used to monitor the fatigue incurred during an exercise set and potentially monitor the exertion of the performer. Finally, augmented feedback can help to further elicit velocity-specific adaptations during training by increasing the movement velocity attained during an exercise in comparison to lifting the
same load without feedback.

2.0.3 Devices with a Velocity-Based Approach

To implement a VBT approach, it is necessary to have access to equipment that can quickly and accurately compute movement velocity. Devices such as linear position transducers (LPTs) [108–110], photogrammetric tools such as video cameras [111] or three-dimensional motion capture systems (mocap), and inertial measurement units (IMUs) [112] can be used to quantify movement velocity. However, the cost, portability, and time constraints associated with data processing limit the utility of some of these methods [18, 113]. Therefore, LPTs, and more recently IMUs, have become popular for researchers and exercise professionals to quantify movement velocity in an exercise setting.

Linear Position Transducers

String potentiometers or rotary encoders are LPTs typically used in the field to record an object’s position data [108]. String potentiometers measure the position of an object via a rotation sensor attached to a flexible cable and a spring loading spool. A small wiper is placed in contact with a track on the rotation sensor, and this wiper is connected via the cable to an object (ex. barbell). As the object moves, the extension of the cable rotates the wiper and provides an electrical output (voltage) proportional to the cable’s displacement.

A rotary encoder operates similarly; however, it converts the angular position of a shaft or axle into an analog or digital code. Two light sources and sensors are placed on opposite sides of a concentric ring with several small openings. This concentric ring is attached to a cable, which is also attached to an object (ex. barbell). As the object moves, the concentric ring spins, and the sensors detects voltage “spikes” whenever light passes through the small openings. These small openings are spaced at a fixed angular distance from each other, and the two spikes can be used to distinguish between forward and reverse motion (Figure 2.0.1). Then, depending on the orientation of the two signals, an “up” or “down” count can be produced to capture the position of the object. For example, if one count equates to a 1mm change in linear position, 10 counts “up” would equate to 10mm of displacement in the “up” direction.
The data from each device is recorded at regular intervals, denoted as the sampling frequency and measured in Hertz (Hz) (samples per second). The LPT is connected to a computer via a signal conversion box, and software is used to analyze the data. To calculate velocity, the software computes the derivative of the displacement-time signal. Prior to these calculations, the signal is usually smoothed to limit the influence of noise (i.e. unwanted parts of the signal) when taking the derivative. The most commonly used technique to smooth the data is the 4th Order, zero-lag (dual pauss of 2nd order) Butterworth Low-Pass Filter [114].

LPTs provide a low-cost method of monitoring the velocity of a barbell while performing barbell-based exercises. Some researchers prefer using the raw position signal so that they can use their own code to analyze the data [108, 109]; however, the data smoothing and differentiation process add additional steps that could potentially limit the utility of the device during training sessions. Several commercially available LPTs are equipped with software to quickly compute this information so that the data can be used conveniently during a training session.

**GymAware**

The GymAware (Kinetic Performance Technologies, Canberra, Australia) (GYM) is a commercially available LPT that can provide velocity data during an exercise set. The GYM is built with a digital optical rotary encoder that presents real time velocity data to a tablet via Bluetooth. The GYM uses an adaptive rate sampling frequency, whereby optical pulses from the encoder are fed into a position tracker that keeps track of the current cable position. When a transition occurs, it is time-stamped and recorded with a resolution of 35 microseconds. Points are only recorded when the position of the tether changes by 600 µm. This removes the noise associated with quantization and periodic sampling with traditional methods. A more detailed explanation of this adaptive rate sampling process used by GYM can be found in a paper by Qaisar et al. [115]. Due to this sampling method, the data is not smoothed. Velocity is computed by differentiation of the position-time signal. Additionally, the GYM includes an angle sensor for exercises that do not have a straight, non-curvilinear vertical trajectory. The raw position data and the angle sensor produce polar coordinates that can be used to determine the vertical velocity of an object.

There are currently a few studies that have validated the GYM for the calculation of MV and PV with barbell exercises such as the back squat and bench press. Banyard et al. [19] assessed the validity of the GymAware in the back squat. Participants performed three repetitions at 20, 40, and 60%1RM, and one repetition at 80, 90 and 100% 1RM on two separate occasions. Following successful 1RM attempts, the load was increased by 0.5-2.5kg until no further weight could be lifted, with a maximum of five total attempts permitted. The mean and peak velocity data were compared to that of a four-LPT lab system (Celesco PT5A-250; Chatsworth, California, USA) mounted on the top anterior and posterior parts of the squat rack. By placing the four LPTs in this manner, the horizontal and vertical components of the barbell could be captured, providing a more accurate measure of the displacement of the central position of the barbell. The validity of each device was determined at 20-100% 1RM in 10% increments. It was found that GYM was valid for measuring mean and peak velocity (\( r > 0.7 \) cutoff point, \( COV < 10\% \) cutoff point, and effect size <\( 0.6 \) cutoff point). However, the velocities associated with each relative load were not reported. Although participants were encouraged to lift as fast as they could, it is possible
that some participants lifted a heavier load faster than another participant lifted a lighter load. Since the validity of the device may be influenced by the movement velocity (e.g., signal-noise ratio larger at very slow or very fast movement velocities), it is difficult to draw definitive conclusions from this study.

One other experiment has been performed internally by GYM [116]. In relation to a Calibration Rig, which is a device used for the calibration of dynamometry equipment, the GYM was shown to be a valid and reliable device for measuring vertical displacement, mean velocity, and peak velocity for mean velocities ranging from 0.30-1.60 m s$^{-1}$. Although this study included the velocities tested, the analysis was not based on the velocities attained, and therefore it is still impossible to determine whether the GYM is valid at all tested velocity ranges. In addition to Banyard et al. [19] and Youngson [116], other authors have found the GYM to be a valid tool to measure power [117, 118].

Therefore, it appears that the GYM can be considered a valid device for monitoring the velocity of free-weight back squats and linear trajectories when the mean velocity of the lifting phase is between 0.30-1.60 m s$^{-1}$. However, due to the fixed linear movement and limited velocities tested with the Calibration Rig during the internal validation study [116], there is no current data that tests the validity of the GYM during a wide range of movement velocities (i.e. <0.3 m s$^{-1}$ and >1.6 m s$^{-1}$) during a free-weight, barbell exercise. Additionally, there is currently no data that analyzes the validity of the GYM as a function of the movement velocity. Banyard et al.’s investigation [19] assessed the validity of the GYM at relative loads of 20-100% 1RM. However, VBT regulates intensity by movement velocity and not %1RM, and it is also possible to move a light relative load with a slow movement velocity. Therefore, future analysis should assess the validity of these tools as a function of the actual movement velocity so that results can be extrapolated to VBT.

**Tendo**

The Tendo Power Analyzer (TENDO Sports Machines, Trencin, Slovak Republic) (TEN) is another commercially available LPT that can compute velocity data. Similar to the GYM, the TEN is an optical rotary encoder and its sampling frequency is determined by the concentric ring’s rotation. Velocity is also computed via differentiation, and these data are uploaded to the TEN microcomputer. The TEN does not have an angle sensor, and thus cannot correct for movements that do not follow a straight, non-curvilinear vertical trajectory.

Despite this apparent limitation, studies have demonstrated that TEN is a valid tool for certain velocity measures and movements. The TEN displayed high intraclass-correlation coefficients (ICC), low systematic differences, and low average random errors in comparison to a criterion LPT (T-Force LPT- collecting at 100Hz, filtered at 10Hz) [20]. For this investigation, 71 men with at least three years’ experience with resistance training performed four sets of a back squat and bench press. For each exercise, four repetitions were performed with a 40kg load, three repetitions with a 50kg, two repetitions with a 60kg load, and as many repetitions as possible with an 85%1RM load. During the back squat, the TEN was valid for MV ($r=0.985$, $p<0.01$, random error= ±0.07 m s$^{-1}$) and PV ($r=0.963$, $p<0.01$, random error= ±0.12 m s$^{-1}$). Similar findings were reported for the bench press. When assessing the test-retest capabilities of the TEN, high ICCs were reported for the squat and bench press (ICC= 0.966-0.988) for MV and PV. Minimal systematic errors (0.07-0.13 m s$^{-1}$) were reported across the tested
velocities, as well as no evidence of a proportional bias (COV=9.1-9.3%). The authors concluded that the TEN presented adequate concurrent validity and test-retest reliability to be used to monitor and assess barbell velocity while performing the back squat and bench press. However, it is important to note that this study used a Smith-Machine, and thus the trajectory of the barbell was fixed. Since the trajectory of the barbell may not be straight/non-curvilinear during a free-weight exercise and the TEN does not have an angle sensor, this study provides limited ecological validity for researchers or exercise professionals that may use free-weight exercises in studies or training programs. Additionally, the movement velocities were not reported directly in this study. For the same reasons stated above, this limits the applicability of these findings for VBT since the validity was not determined for a range of velocities, but for a range of loads.

In relation to a motion capture system, the TEN has shown to be a valid tool to measure mean velocity of a back squat within a range of 0.09-0.85 m s$^{-1}$, but not peak velocity within a range of 0.29-1.54 m s$^{-1}$ [23]. In this thesis work by Goldsmith, 25 males performed a 1RM back squat test. Participants performed five repetitions with 20% of their 1RM, then three repetitions at 50% 1RM, two repetitions at 75% 1RM, and one repetition at 85% 1RM. The investigations cited do not use a large range of tested velocities, nor does the analysis consider if the movement velocity can influence the validity of a device. It is possible that devices are less valid at certain velocity ranges than others, which is not highlighted when assessing all repetitions with one analysis. More research is required to consolidate whether the TEN is a valid device for measuring barbell velocity during free-weight, barbell exercises for a wide range of velocities.

Inertial Measurement Units

Another device that can be used to quantify exercise velocity is an Inertial Measurement Unit (IMU). An IMU is composed of an accelerometer, a gyroscope, and sometimes a magnetometer. The accelerometer measures linear acceleration in up to 3 axes with either a piezoelectric effect (stress of microscopic crystals causes a voltage to be generated) or by the capacitance between two microstructures. The gyroscope provides angular velocity and orientation data. However, IMUs are susceptible to drift (i.e. change in the signal), and require that the original orientation of the object be known as they can only react to changes in acceleration. A magnetometer can be used to accommodate this limitation by detecting the earth’s magnetic field, however they are not as well-suited for faster movements. In these devices, the voltage data can be transferred to another device where software can process and analyze the signal, similar to that of LPTs. Although the signal may be smoothed in a similar manner, velocity is calculated by integrating the acceleration-time signal.

There are several advantages to using IMU-based velocity sensing devices in a training setting. First, they are typically lower-cost than LPTs. For example, the GYM and TEN currently sell for $2200 USD and $1329 USD, respectively. Although LPTs are lower-cost than most optoelectronic motion capture systems, an IMU device sold by PUSH$^\text{TM}$ currently sells for approximately a tenth of the cost. Second, IMUs are more portable than LPTs, and do not have to be placed underneath or above the athlete, which is desirable for exercise professionals and researchers with limited floor space. Third, an IMU will not be limited by the displacement of a barbell or a performer during certain movements, which may be an issue with using a cable-based LPT (ex. if performing a barbell clean and jerk). Finally, an IMU
that can measure both linear and rotational motion are not limited to only linear motion as an LPT would be.

**PUSH**

An example of an IMU being used to monitor velocity data is the PUSH™ device (PUSH Inc, Toronto, Canada) (PSH). PSH is an IMU that is worn on the proximal forearm and contains a 3-axis accelerometer and a single gyroscope. It uses a sampling frequency of 200Hz and a zero-lag, 4th order Low-Pass Butterworth Filter to smooth the data. Proprietary algorithms are then used to convert the linear and angular accelerations of the proximal forearm into the linear velocity of the barbell. This data is sent via Bluetooth to a smartphone or tablet application.

There are currently four studies that have examined the validity of the PSH device. Banyard et al. [19] assessed the validity of the PSH device concurrently with the GYM. The authors found that at relative loads lower than 80%1RM for MV and equal to 20%1RM for PV, PSH was deemed to be valid ($r > 0.7$, COV $\leq 10\%$, and ES $< 0.6$) compared to the criterion LPTs (Celesco PT5A-250; Chatsworth, California, USA). Additionally, the validity of the PSH device, as determined by its correlation coefficient and the CV%, decreased as the load increased towards 100%1RM. The authors concluded that the PSH device was not a valid tool to measure mean or peak velocity in the back squat, especially at higher loads greater than 80% for MV and 20% for PV. As highlighted previously, this study assessed the velocity of the device at a range of relative loads rather than with a range of velocities, making it difficult to interpret the validity of the device if being used in a VBT program where velocity would be manipulated for desired training effects.

Sato et al. [21] analyzed the validity of the PSH device relative to a three-dimensional motion capture system during a dumbbell overhead press and a dumbbell biceps curl. Five participants performed four sets of ten repetitions with a light-to-moderate load for each exercise. They found that for the dumbbell shoulder press, the typical error (TE), relative typical error RTE), t-test p-value, and correlation coefficient ($r$) for MV-PV data were TE=0.090-0.163, RTE=12.6%-14.0%, $p< 0.0001$, and $r=0.864-0.801$ at velocities ranging from approximately 0.50-1.50 m s$^{-1}$ and 0.75-2.00 m s$^{-1}$, respectively. Similar values were reported for the biceps curl. The authors concluded that PSH was valid for a dumbbell bicep curl and overhead press for MV, contradicting the findings of Banyard et al. [19]. It is important to note that this study did not test a range of movement velocities as two loads (4.54 kg and 6.82 kg) were used for each exercise and the authors did not state how the participants were cued to lift each load. In addition to analyzing exercises not commonly used by exercise professionals in a performance training setting and the loads being manipulated rather than the velocity, interpretation of these results is difficult.

In a third study [18], the PSH device was compared to a criterion LPT (T-Force Dynamic Measurement System, Ergotech, Murcia, Spain). Ten physically active sports science students performed a back squat on a smith machine with loads of 20, 40, 50, 60, and 70kg. A large association ($r=0.86$ and $0.91$, $p< 0.001$, SEE= 0.08m s$^{-1}$-0.1m s$^{-1}$), and agreement (ICC= 0.907-0.944) was found, as well as a systematic bias for the PSH (+0.11 ± 0.1m s$^{-1}$, -0.07 ± -0.1m s$^{-1}$) for MV and PV data. The authors concluded that the device was valid in measuring MV data between approximately 0.35-1.20m s$^{-1}$ and PV data between approximately 0.70-2.30m s$^{-1}$. However, the findings from this study raise some questions
since the bias for MV was found higher than that of the LPT, but the PV bias was lower than that of the LPT. There was no justification as to why MV values would be overestimated but PV values would be underestimated. Furthermore, this study was also conducted on a Smith Machine, limiting the ecological validity of the findings. Finally, the loads were manipulated to determine the validity of the device rather than the actual movement velocity, making the findings difficult to interpret when velocity may be prioritized during exercise.

Finally, a study conducted by Orange et al. [22] investigated the validity of the PSH device relative to a GYM during a squat and bench press. Twenty-nine professional male youth rugby league players performed three consecutive repetitions with 20, 40, 60, and 80%1RM while being instructed to move as fast as possible. In their investigation, a Pearson $r$ of $<0.5$ was considered poor, 0.75-0.89 good, and $\geq0.9$ excellent, with confidence intervals set at 95%. For the back squat, it was found that PSH demonstrated moderate to very large underestimations of MV at each load. Additionally, good (0.75-0.89) correlations were found for MV at 20, 60, and 80%1RM and for peak velocity at 20 and 80%1RM. For the bench press, small systematic biases were found for MV at 60%1RM, and peak velocity at 20 and 40%1RM. There were moderate differences found between GYM and PSH for all other compared loads for both mean and PV. Good (0.75-0.89) correlations were found for mean velocity at 40%1RM ($r=0.89$, CI: 0.77-0.95). Other MV and PV data at all other tested loads were not found to be valid. However, this study suffers similar limitations as the previously mentioned studies as it had assessed the validity of the device by manipulating the relative load lifted and not the actual movement velocity. Also similar to the other studies, the actual movement velocities were not explicitly reported.

**Summary of Devices for Velocity-Based Training**

It is critical that the devices used for monitoring movement velocity be valid, or at the very least reliable, to make appropriate inferences during training. Due to monetary and practical constraints, commercially available LPTs and IMUs are best suited for collecting this data. Although the GYM appears to be a valid LPT for measuring movement velocity, current research on the TEN and PSH is not as conclusive. However, all studies to date have assessed the validity of these devices while manipulating the load lifted rather than manipulating the movement velocities. This, along with the limited reporting of explicit movement velocities, has resulted in analyses that have not tested a wide range of velocities that may be used with VBT and do not evaluate if the devices are valid at certain velocity ranges and not others. Since many of these studies also do not use free-weight exercises, future research examining the validity of these devices for a wider range of movement velocities, as a function of the actual movement velocity and not the relative load lifted, needs to be conducted with free-weight exercises.

**2.0.4 Velocity Data Collection and Analysis**

In the literature, the implementation of VBT has been based solely on absolute velocities (ex. $1\text{m s}^{-1}$). For example, Gonzalez-Badillo et al. [3] suggested that movement velocities should be used to prescribe and monitor training loads. It has also been recommended that absolute velocities (ex. $1.0\text{m s}^{-1}$, $0.40\text{m s}^{-1}$, etc.) be used to prescribe training loads [2]. There have also been absolute mean velocities cited to target specific training adaptations [119]. However, this may not necessarily be appropriate for all applications.
In a group of football players, it was determined that the maximum velocity attained with loads less than 55% 1RM, which would likely be used when prioritizing fast movement velocities, are a difficult metric to reproduce over time [29]. Therefore, an athlete’s maximum velocity may fluctuate daily, similar to maximum strength. In addition to day-to-day fluctuations in maximum velocity within a performer, there may also be differences in maximum velocity capabilities between performers. For example, in unpublished data from varsity football athletes, the peak velocity attained with a wooden dowel (approximately 0.26kg) was $4.23 \pm 0.68 \text{m s}^{-1}$, with velocities ranging from 2.47-5.24m s$^{-1}$. This discrepancy in maximum velocity attainment highlights the potential implications of prescribing an absolute mean velocity for a group of athletes; the prescription of absolute velocities when fast movement velocities are emphasized may therefore be analogous to prescribing absolute loads when large external loads are emphasized during training.

When prioritizing faster movement velocities in training, it may therefore be more appropriate to use relative velocities instead of absolute velocities. A relative velocity would be based on a maximum velocity a performer could attain that specific day. This would also accommodate to changes in maximum velocity over time, as well as the capabilities of each individual performer. Repetitions could be performed as fast as possible with a wooden dowel for barbell-based movements to establish a daily maximum velocity without putting excessive strain on the performer. Then, a percentage of this maximum velocity, below or above 100% depending on whether resisted or assisted training will be performed, can be assigned during training. Although this method of assigning movement velocities has not yet been tested, it may offer some benefits when attempting to autoregulate training when faster movement velocities are prioritized.

2.0.5 Integration of Instruction and Feedback with Velocity Data

In addition to autoregulating training intensity assessing fatigue and effort, VBT may provide an opportunity to utilize augmented feedback to enhance training. Providing feedback in a practice or training setting is critical for the acquisition of various motor skills [120]. In general, there are two specific methods of providing qualitative or quantitative knowledge of results (KR) [120]. In the case of providing velocity feedback, this would be an example of quantitative KR. Previously, researchers or exercise professionals may have provided qualitative KR by subjectively monitoring barbell velocity. Quantitative KR provides a more objective form of feedback for performers.

Most practitioners will instruct their athletes to move as fast as possible during the lifting phase of an exercise to ensure they are exerting a maximum effort [52]. Because a combination of qualitative and quantitative KR can result in superior skill acquisition [120], it may be possible to use velocity data and verbal encouragement to further enhance the athlete’s movement velocity to provide superior training adaptations. Two papers have investigated the use of quantitative KR (in the form of movement velocity) following each repetition of a jump squat. This feedback during training decreased the variability in the velocities attained relative to not receiving any feedback, and appeared to enhance vertical and horizontal jump performance adaptations, as well as reduce sprint times [25]. Although quantitative KR was provided, there was no instruction provided as to whether to attain any specific velocity target.
Receiving velocity feedback during a training session also allows for the establishment and pursuit of goals within a workout. Exercise professionals can both assign goals for the athlete to achieve, while the quantitative KR allows the athlete to know if they are moving “fast enough”. Goal-setting theory, originally introduced by Locke and Lathan [27] suggests that these goals can provide motivation for athletes to attain higher levels of performance. When more difficult goals are set, there is the potential for increased performance [26], so long as the limits of one’s ability are not already reached or the commitment to the goal has not lapsed [121]. It was found that specific, difficult goals led to higher performances than urging people to “do their best” [26]. This may stem from not having an external reference, and thus “doing their best” is defined idiosyncratically [28]. In the context of VBT, this is paralleled by providing athletes with a velocity-oriented goal versus encouraging them to move as fast as possible.

Therefore, there may be opportunity to use velocity data to provide quantitative KR, and to set personalized goals during training to improve performance. A way this can be done is to provide a challenging target velocity to a group of athletes, while providing feedback of their movement velocity during a workout. With this approach, they would be receiving quantitative KR through the real-time velocity feedback while also striving to reach a challenging goal. Theoretically, setting challenging target velocity goals and providing augmented velocity feedback could prompt athletes to move faster and enhance velocity specific adaptations. However, this type of instruction has not yet been evaluated. Therefore, future research should evaluate the kinematic changes in bench press performance following the implementation of this instruction to determine its efficacy for improving upon velocity-specific training adaptations.

2.0.6 Conclusions

When trying to develop speed and power in athletes, there are several important factors that researchers and exercise professionals should consider. Prioritizing the movement velocity of the exercise, as well as the intent to move as fast as possible, appears to be beneficial for velocity-specific training adaptations, which may stem from a variety of central and peripheral adaptations. Additionally, if utilizing a velocity-based approach, the potential exists to autoregulate the intensity of training by estimating %1RM. However, this may not be best suited for applications where determining an accurate 1RM is important (i.e. strength sports, 1RM tests). Previous research examining training programs that have assigned training loads based on movement velocity have found promising speed- and power-related adaptations. Furthermore, feedback of a performer’s movement velocity can also be used to monitor fatigue and effort during training.

When collecting velocity data to use for feedback in research settings or with exercise professionals, it is important to use valid tools. Although there are several valid laboratory-grade systems, they are often too expensive or impractical for a gym setting. Therefore, LPTs and IMUs offer a practical alternative for monitoring exercise velocity. Three commonly used devices are the GYM, TEN, and PSH. Based on the previous literature, it appears that the GYM is a valid device for monitoring exercise velocity, whereas the TEN and PSH have conflicting findings. However, all previous studies have the same limitation in that the loads were manipulated to assess the validity of the devices rather than the velocities. Since “lighter” loads could theoretically be lifted at the same velocity as heavier loads, it is difficult to discern
whether these devices are valid during very slow, very fast, or intermediate velocities, especially when the actual movement velocities were not reported in the studies. Future research needs to assess the validity of these devices based on the movement velocity instead of the load being lifted.

Furthermore, if prioritizing movement velocities during training, the common method has been assigning loads based on an absolute velocity (i.e. $1.0 \text{m s}^{-1}$). However, there are a variety of kinematic, muscle activation patterns and muscle fiber characteristics that may influence the maximum velocity that a performer can attain. It also appears that a maximum velocity is a difficult performance parameter to reproduce, and therefore may fluctuate between training sessions. Therefore, the current practice of prioritizing movement velocity with absolute velocities may be inappropriate. Future research should be conducted to assess the potential implications of training with absolute versus relative velocities on the training intensity of individuals.

Finally, receiving feedback of a performer’s movement velocity allows researchers and exercise professionals to provide knowledge of results, which may benefit the acquisition of the skill to move as fast as possible. Additionally, this feedback allows practitioners to provide difficult goals in the form of velocity targets for their athletes to acutely improve movement velocity. Future research should examine utilizing challenging target velocities as an instruction to examine if this method of providing feedback facilitates faster movement velocities during exercise.
Chapter 3

Investigation I
Validity of GymAware, Tendo, and PUSH During a Free-Weight Bench Press

3.0.1 Introduction

Training variables, such as the frequency, intensity, and type of exercise are strategically manipulated to elicit specific short- and long-term training adaptations [31–33]. Although the exercise frequency, type, and time can be easily controlled, regulating intensity has proven to be a complex problem. Typically, training intensity is defined relative to one’s maximum strength (%1RM) [4, 5], established via direct measurement (ex. 1RM test) or indirect estimation (ex. repetition maximum test) [6]. However, inherent to this approach is an assumption that maximum strength remains consistent between days throughout the training cycle, even though several factors can influence an individual’s training state (ex. fatigue [7], psychological stress [8], hydration status [9], and diet [10]). In many instances, these tests may also be impractical or increase the risk of injury if performed each training session [3, 92]. To regulate training intensity and accommodate to the potential between-day variability in maximum strength, researchers have proposed that training intensity be regulated based on a performer’s state of readiness [2].

Several researchers have suggested that a velocity-based approach, whereby movement velocity is used to regulate training intensity, would be a practical and less risky method of accommodating to fluctuations in maximum strength compared to consistent maximum strength testing [3]. Provided that the lifting (i.e. concentric) phase of an exercise is executed as fast as possible, the mean concentric velocity can be used to estimate 1RM [3, 12–15]. Feedback regarding the maximum velocity that was attained may help to regulate effort [24, 25], monitor fatigue within an exercise set [107], and be used to assign training loads [3, 122].

However, the utility of this velocity-based approach depends on the validity of the equipment being used to monitor mean and peak velocity. Devices such as linear position transducers (LPTs), video cameras, three-dimensional motion capture systems (mocap), and inertial measurement units (IMUs) can be used to quantify velocity during exercise. Factors such as cost, portability, and time constraints limit the practical application of many of these devices. In practice, LPTs and IMUs are the most commonly used tools due to their reasonable price, ease of use, and ability to provide data in a timely manner. For example, the Tendo Power Analyzer (TEN) and GymAware (GYM) are two LPTs commonly used by exercise professionals to monitor barbell velocity in a training session. Additionally, PUSH™ (PSH) have created a wearable IMU that provides near real time velocity feedback during exercise via their integrated mobile device application. The IMU is attached to a band worn on the forearm, and the application uses proprietary algorithms to calculate velocity of the selected upper or lower body exercise.

Previous studies tended to conclude that the devices are valid for monitoring mean and peak exercise velocity (r= 0.801-0.988, COV < 10%, ICC= 0.907-0.988) [18–21, 116]. However, Goldsmith reported that the TEN device computes valid mean velocity data, but not peak velocity data [23]. Banyard et al. suggest that the PSH device was not valid, especially at higher relative loads (which implies slower movement velocities) [19]. Additionally, Orange et al. [22] reported that the PSH was valid at monitoring back squat mean velocity at 20, 60, and 80%1RM and peak velocity at 20 and 80%1RM, as well as bench press mean velocity at 40%1RM. Other than this, PSH was not valid at computing
mean or peak velocities at loads ranging from 20-80%1RM in 20% increments. However, there is limited evidence documenting the validity of the TEN, GYM, and PSH across a wide spectrum of movement velocities. All previous work has manipulated the load lifted to assess the validity of each device rather than explicitly testing a specific battery of movement velocities. Since “lighter” loads could theoretically be lifted at the same slow velocity as a heavier load (if consciously trying to lift “slowly”), it is difficult to discern whether these devices are valid during very slow, very fast, or intermediate velocities. This is important since the validity of the devices could be influenced by the actual movement velocity being measured. Additionally, conducting studies with free-weight exercises is also needed to maximize the ecological validity of each device for practitioners. This is especially important for the PSH device since it is worn on the forearm, and thus the barbell velocity must be computed with proprietary algorithms and a non-linear trajectory.

Therefore, the purpose of this study was to assess the validity of the GYM (Kinetic, ACT, AU), TEN (Tendo Sports Machines, TC, SK), and PSH (PUSH Inc, ON, CA) while performing a free-weight barbell bench press, with movement velocities ranging from $<0.40\text{m s}^{-1}$ to $>1.8\text{m s}^{-1}$. A three-dimensional motion capture system was used for comparisons.

### 3.0.2 Methodology

**Experimental Approach to the Problem**

Participants attended two testing sessions (Session A and Session B) separated by 3-7 days. Each session involved a general and specific warm-up, a maximum velocity test at 0% 1RM, a 1RM test, four sets of 5 repetitions at 45% 1RM performed as fast as possible, and a repetition maximum test at 75% 1RM. Mean and peak velocity of all repetitions were recorded with GYM, TEN, and PSH and were compared to that from a three-dimensional motion capture system. Velocity of the barbell was measured directly with mocap, GYM, and TEN, indirectly with the PSH device (Figure 3.0.1). The linear association (correlation) between each device and the mocap was determined along with the average relative error of each device relative to mocap. This measure was used to ensure that the errors produced by each device did not exceed a pre-specified tolerance and that errors across different velocity ranges were expressed in a manner that could be compared.

**Participants**

Eight male powerlifters (3.0.1) who had completed at least one sanctioned competition prior to the commencement of the study were recruited to participate. This study was approved by the ethical review board of the university. Participants signed an informed consent and a PAR-Q and YOU form prior to the commencement of testing.

| Table 3.0.1: Participant characteristics for Investigation I. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Age             | Height          | Mass            | Years Training  | Years Competing | 1RM             |
| 25.1 ± 4.60     | 1.77 ± 0.06m    | 86.1 ± 12.0kg   | 7.88 ± 5.33     | 2.00 ± 0.53     | 143 ± 23.0kg    |
Figure 3.0.1: Picture of instruments used for the study. Depicted are the three motion capture cameras, the GymAware and Tendo (right side of barbell), the PUSH (right arm of the participant), and the retroreflective markers placed on the barbell.

Procedures

Upon arrival for the first testing session, participants were given five minutes to perform their own preferred low intensity warm-up and/or flexibility routine. This warm-up was documented so that the same protocol could be used prior to the second testing session. Following the participants’ warm-up, they were given the following instructions: 1) each repetition must be performed without pausing between the lowering (eccentric) and lifting (concentric) phases of the bench press; 2) the barbell must come within 0.05m of the chest without touching; 3) if the barbell touches the chest or fails to be lowered within 0.05m of the chest, the repetition will be disregarded; and 4) both feet must remain in contact with the ground, and the head, upper back and hips must remain in contact with the bench at all times. Prior to the commencement of any bench press exertions, participants’ grip and foot width were self-determined and marked for future reference. Both measurements were kept consistent throughout testing. If any repetition was disregarded, participants received feedback as to why it did not meet the study criteria, and then were given five minutes rest to repeat their 1RM attempt. Participants were not given an opportunity to repeat any attempts during sub-maximal testing.

Once briefed on the study protocol, a standardized warm-up with the barbell was performed. Participants performed five repetitions with an unloaded barbell (20kg), and 35% and 50% of an estimated 1RM. Two minutes rest was provided between each set. Participants then performed a maximum velocity test with a wooden dowel (approximately 0.26kg) to estimate their maximum velocity (i.e. 0% 1RM). Participants performed three repetitions as fast as possible with the dowel, each separated by 30 seconds of rest.
Using a protocol similar to Frost et al. [30], participants then progressed to a 1RM bench press test. Briefly, participants performed one set of four repetitions with 60% of an estimated 1RM, one set of three repetitions with 70% of an estimated 1RM, one set of two repetitions with 80% of an estimated 1RM, and one set of one repetition with 90% of an estimated 1RM. They were then given a maximum of five attempts to determine their 1RM. Three minutes rest was provided between each set with loads less than 90% of the estimated 1RM, and five minutes rest was provided for all sets exceeding 90% of the estimated 1RM.

Following the 1RM test, participants were given five minutes rest prior to beginning the sub-maximal “velocity” test at 45% 1RM. This test included four sets of five single repetitions (i.e. the barbell was racked following each repetition). Fifteen seconds and three minutes rest was given between each repetition and set, respectively. Upon completion of these four sets, participants were given five minutes rest prior to performing a repetition maximum test with 75% of their tested 1RM (i.e. as many repetitions as possible within a single set). Participants returned for a second testing session 3-7 days later. The only difference was the instruction provided during the 4 sets of 5 single repetitions. These loads were chosen to accommodate the objectives of Investigation II and also provide a wide spectrum of movement velocities for analysis.

Data Collection and Analysis

The mean and peak velocity of each repetition was computed with a three-dimensional motion capture system (Optritrack Flex 13, NaturalPoint Inc., Corvallis, OR, USA), GYM, TEN, and PSH. A spherical retroreflective marker was placed on the center of the barbell and wooden dowel to monitor the center position of the barbell. ADTech Motion Analysis Software System (AMASS; C-Motion, MD, US) was used to quantify the three-dimensional location of this retroreflective with three OptiTrack Flex 13 Cameras (NaturalPoint Inc, OR, USA) while sampling at 120Hz. Marker displacement data was smoothed with a 4th order, zero-lag Butterworth low-pass filter in Visual3D (C-Motion, MD, US) with an effective cut off-frequency of 10Hz. Event detection algorithms were used to objectively define the bottom and top position of each repetition by detecting the global minimum and maximum vertical positions. Mean velocity of the lifting phase was computed by dividing the vertical displacement of the lifting phase by the time taken to completion. Peak velocity of the lifting phase was determined by differentiating the vertical component of the displacement-time curve and extracting the maximum instantaneous velocity at any point during the repetition.

The GYM was attached to the right collar of the barbell, and magnetically mounted to the floor with a metal 5kg weight plate to ensure the LPT remained grounded throughout all repetitions. The TEN was attached on the outside portion of the right collar of the barbell. Both devices were placed directly beneath the barbell when the participants performed their bench press repetitions to minimize any forward/backward displacement of the LPT cord. The PSH device was affixed to the right proximal forearm, in the direction and orientation suggested by the PSH device manual. A picture of this setup can be viewed in Figure 3.0.1. Velocity for the GYM and TEN unit was determined via proprietary software that ultimately differentiated the displacement-time signal of the concentric portion of the bench press repetition. The velocity of the PSH device was determined via proprietary algorithms that ultimately integrated the vertical acceleration-time signal.
Statistical Analysis

The validity of mean and peak velocity data from each commercial device relative to the mocap was analyzed separately. Only repetitions in which all four devices (i.e. Mocap, GYM, TEN, and PSH) recorded a velocity was used in the analyses. Each repetition was categorized into one of four bins based on the mean and peak velocity computed with the motion capture system. The four mean velocity bins were $MV \leq 0.40 \text{m s}^{-1}$, $0.80 \leq MV > 0.40 \text{m s}^{-1}$, $1.20 \leq MV > 0.80 \text{m s}^{-1}$, and $MV > 1.20 \text{m s}^{-1}$, and the four peak velocity bins were $PV \leq 0.60 \text{m s}^{-1}$, $1.20 \leq PV > 0.60 \text{m s}^{-1}$, $1.80 \leq PV > 1.20 \text{m s}^{-1}$, and $PV > 1.80 \text{m s}^{-1}$. These ranges were chosen to have a similar number of data points in each bin. Pearson correlation coefficients ($r$) and the average absolute error of each device relative to the motion capture velocity were calculated in each bin to determine the validity of each device across a spectrum of movement velocities (ex. If PSH = 2.00 m s$^{-1}$ and MCP = 1.50 m s$^{-1}$ the absolute error = 0.50 m s$^{-1}$, relative error = 33.3%). For a device to be considered valid for a specific velocity range, the Pearson correlation coefficient must exceed 0.7 and the mean error relative to motion capture must be equal to or less than 10%. The basis of this criteria was determined based on the Pearson correlation coefficient and the coefficient of variation cut-offs used in previously published literature [19]. The bias (i.e. average error) of each device in comparison to the motion capture was also computed. All statistical analyses were performed with the R programming language.

3.0.3 Results

A total of 580 and 548 repetitions were assessed for MV and PV, respectively. Recorded mean and peak velocities with the motion capture ranged from 0.06-2.43 m s$^{-1}$ and 0.21-3.62 m s$^{-1}$, respectively. For the MV bin ranges of $MV \leq 0.40 \text{m s}^{-1}$, $0.80 \leq MV > 0.40 \text{m s}^{-1}$, $1.20 \leq MV > 0.80 \text{m s}^{-1}$, and $MV > 1.20 \text{m s}^{-1}$ there were 113, 311, 130, and 26 data points, respectively (Table 3.0.2). For the PV bin ranges of $PV \leq 0.60 \text{m s}^{-1}$, $1.20 \leq PV > 0.60 \text{m s}^{-1}$, $1.80 \leq PV > 1.20 \text{m s}^{-1}$, and $PV > 1.80 \text{m s}^{-1}$ there were 115, 223, 174, and 36 data points, respectively (Table 3.0.3). Other participant data is outlined in Table 3.0.1.

GymAware

The GYM was found to meet the validity criteria for all MV ranges ($r = 0.92-0.98$, average relative error= 5-7%) with the exception of that above 1.2 m s$^{-1}$ ($r = 0.87$, average relative error= 13%) (Table 3.0.2). It also consistently overestimated movement velocities, with a larger bias occurring at faster MVs (Table 3.0.2). Qualitatively, the magnitude of errors increased with an increase in MV (Figure 3.0.2). The GYM met the validity criteria for all PV ranges ($r = 0.96-0.97$, average relative error= 2-6%) (Table 3.0.3), but overestimated PV when less than 1.2 m s$^{-1}$, and underestimated PV when greater than 1.2 m s$^{-1}$.

Tendo

The TEN was found to meet the validity criteria for the MV bin ranges of $MV \leq 0.40 \text{m s}^{-1}$ and $0.80 \leq MV > 0.40 \text{m s}^{-1}$ ($r = 0.94-0.95$, average relative error = 10% in both bins) (Table 3.0.2). Similar to the GYM, TEN overestimated MV, with larger discrepancies occurring at higher MVs. Figure 3.0.2 shows that the magnitude of errors also increased with MV. The TEN was found to be valid for all
PV bin ranges \( r=0.90-0.94 \), average relative error= 7-9%), but also underestimated PV, with larger differences occurring at higher velocities (Table 3.0.3).

**Push**

PSH did not meet the validity criteria for any of the MV \( r=-0.652-0.616 \), average relative error= 13-44%) or PV \( r = 0.36-0.52 \), average relative error = 15-28%) bins (Table 3.0.2 and Table 3.0.3). PSH tended to overestimate MV \( \leq 0.40 \) m s \( ^{-1} \) and underestimate MV \( >0.40 \) m s \( ^{-1} \) (Table 3.0.2). PSH also overestimated PV \( \leq 0.60 \) m s \( ^{-1} \) and 1.80\( \leq PV > 1.20 \) m s \( ^{-1} \), but underestimated 1.20\( \leq PV > 0.60 \) m s \( ^{-1} \) and \( >1.80 \) m s \( ^{-1} \) (Table 3.0.3). Qualitatively, PSH demonstrated larger errors as the MV and PV increased (Figure 3.0.2 and 3.0.3).

### Table 3.0.2: Pearson \( r \), average error relative to the 3D motion capture, and bias of mean velocity data in all four mean velocity bins for GymAware, Tendo, and PUSH (** = \( p \leq 0.001 \)).

<table>
<thead>
<tr>
<th>Device</th>
<th>Bin (m s ( ^{-1} ))</th>
<th># of Repetitions</th>
<th>Pearson ( r )</th>
<th>Average Relative Error (%)</th>
<th>Bias (m s ( ^{-1} ))</th>
<th>95% CI of Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>GymAware</td>
<td>MV ( \leq 0.40 )</td>
<td>113</td>
<td>0.97**</td>
<td>7.75</td>
<td>-0.013</td>
<td>4.04e-4</td>
</tr>
<tr>
<td></td>
<td>0.80( \leq MV &gt; ) 0.40</td>
<td>311</td>
<td>0.96**</td>
<td>7.34</td>
<td>-0.043</td>
<td>2.44e-4</td>
</tr>
<tr>
<td></td>
<td>1.20( \leq MV &gt; ) 0.80</td>
<td>130</td>
<td>0.92**</td>
<td>5.43</td>
<td>-0.046</td>
<td>6.75e-4</td>
</tr>
<tr>
<td></td>
<td>MV &gt; 1.20</td>
<td>26</td>
<td>0.87**</td>
<td>13.1</td>
<td>-0.209</td>
<td>0.016</td>
</tr>
<tr>
<td>Tendo</td>
<td>MV ( \leq 0.40 )</td>
<td>113</td>
<td>0.95**</td>
<td>9.94</td>
<td>-0.009</td>
<td>4.63e-4</td>
</tr>
<tr>
<td></td>
<td>0.80( \leq MV &gt; ) 0.40</td>
<td>311</td>
<td>0.94**</td>
<td>10.0</td>
<td>-0.060</td>
<td>3.42e-4</td>
</tr>
<tr>
<td></td>
<td>1.20( \leq MV &gt; ) 0.80</td>
<td>130</td>
<td>0.88**</td>
<td>9.5</td>
<td>-0.086</td>
<td>9.48e-4</td>
</tr>
<tr>
<td></td>
<td>MV &gt; 1.20</td>
<td>26</td>
<td>0.83**</td>
<td>14.5</td>
<td>-0.232</td>
<td>0.018</td>
</tr>
<tr>
<td>PUSH</td>
<td>MV ( \leq 0.40 )</td>
<td>113</td>
<td>0.53**</td>
<td>33.2</td>
<td>-0.032</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>0.80( \leq MV &gt; ) 0.40</td>
<td>311</td>
<td>0.62**</td>
<td>12.9</td>
<td>0.007</td>
<td>8.96e-4</td>
</tr>
<tr>
<td></td>
<td>1.20( \leq MV &gt; ) 0.80</td>
<td>130</td>
<td>0.47**</td>
<td>14.7</td>
<td>0.027</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>MV &gt; 1.20</td>
<td>26</td>
<td>-0.65**</td>
<td>43.7</td>
<td>0.860</td>
<td>0.042</td>
</tr>
</tbody>
</table>

### 3.0.4 Discussion

The aim of this study was to assess the validity of the GYM, TEN, and PSH in a free-weight bench press with movement velocities ranging from \( >0.40 \) to \( >1.80 \) m s \( ^{-1} \). The results illustrate that the GYM and TEN were valid across most of the velocity spectrum assessed in this study. Specifically, both devices were valid for PV across all velocity ranges, but the GYM and TEN were only valid for MV equal to or below 1.2m s \( ^{-1} \) and 0.8m s \( ^{-1} \), respectively. The PSH device was not valid for any mean or peak velocity range. Assessing the validity of each device across a range of velocities was a necessary but different approach to that used previously. As a result, making direct comparisons to prior work is somewhat challenging. It was important to assess validity using the actual movement velocity since it is velocity, and not load, that is manipulated with VBT. Additionally, since the errors produced by each device might be magnified by faster movement velocities, it was important to assess each device across a range of velocities. Since the actual movement velocity attained with certain loads is dependent on the individual’s capabilities and their intent to move as fast as possible, assessing the validity of each device based on the load lifted \[19, 22\] is not appropriate.

The findings of this study are mostly similar in relation to the currently published literature examining the validity of these devices. Banyard et al. \[19\] evaluated the validity of MV and PV measures for
Table 3.0.3: Pearson $r$, average error relative to the 3D motion capture, and bias of peak velocity data in all four peak velocity bins for GymAware, Tendo, and PUSH (*= $p < 0.05$, **= $p < 0.001$).

<table>
<thead>
<tr>
<th>Device</th>
<th>Bin (m s$^{-1}$)</th>
<th># of Repetitions</th>
<th>Pearson $r$</th>
<th>Average Relative Error (%)</th>
<th>Bias (m s$^{-1}$)</th>
<th>95% CI of Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$&lt; 0.60$</td>
<td>115</td>
<td>0.96**</td>
<td>5.82</td>
<td>-7.05e-4</td>
<td>5.29e-4</td>
</tr>
<tr>
<td></td>
<td>$0.60 &lt; PV &lt; 1.20$</td>
<td>223</td>
<td>0.97**</td>
<td>3.58</td>
<td>-0.003</td>
<td>3.77e-4</td>
</tr>
<tr>
<td></td>
<td>$1.20 &lt; PV &lt; 1.80$</td>
<td>174</td>
<td>0.97**</td>
<td>2.45</td>
<td>0.017</td>
<td>4.10e-4</td>
</tr>
<tr>
<td></td>
<td>$PV &gt; 1.80$</td>
<td>36</td>
<td>0.96**</td>
<td>5.94</td>
<td>0.081</td>
<td>0.012</td>
</tr>
<tr>
<td>Tendo</td>
<td>$&lt; 0.60$</td>
<td>115</td>
<td>0.93**</td>
<td>8.36</td>
<td>0.018</td>
<td>6.87e-4</td>
</tr>
<tr>
<td></td>
<td>$0.60 &lt; PV &lt; 1.20$</td>
<td>223</td>
<td>0.94**</td>
<td>6.96</td>
<td>0.040</td>
<td>5.88e-4</td>
</tr>
<tr>
<td></td>
<td>$1.20 &lt; PV &lt; 1.80$</td>
<td>174</td>
<td>0.90**</td>
<td>7.69</td>
<td>0.099</td>
<td>8.04e-4</td>
</tr>
<tr>
<td></td>
<td>$PV &gt; 1.80$</td>
<td>36</td>
<td>0.94**</td>
<td>9.28</td>
<td>0.236</td>
<td>0.015</td>
</tr>
<tr>
<td>PUSH</td>
<td>$&lt; 0.60$</td>
<td>115</td>
<td>0.44**</td>
<td>24.6</td>
<td>-0.045</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>$0.60 &lt; PV &lt; 1.20$</td>
<td>223</td>
<td>0.52**</td>
<td>14.5</td>
<td>0.049</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>$PV &gt; 1.20$</td>
<td>174</td>
<td>0.58**</td>
<td>15.0</td>
<td>-0.007</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>$PV &gt; 1.80$</td>
<td>36</td>
<td>0.36*</td>
<td>27.7</td>
<td>0.887</td>
<td>0.042</td>
</tr>
</tbody>
</table>

both the GYM and PSH using 10 participants with loads ranging from 20-100% 1RM on two separate occasions. The GYM and PSH data were compared to that of a lab-based, four-LPT system positioned on the anterior and posterior sections of the top of a squat rack. Although the authors did not report the specific correlation coefficients, they did conclude that the GYM was valid, meaning the $r$ value was at least greater than 0.70 (the minimum $r$ value required to be “valid” in the study). Based on a visual assessment of the author’s published data, it appears that the correlation coefficients were at least 0.9 for both mean and peak velocity. This aligns with the $r$ values reported for all mean and peak velocity bins for GYM in this investigation, except that of $> 1.2$ m s$^{-1}$ ($r=0.87$).

Garnacho et al. [20] evaluated the validity of the TEN with seventy-one men performing back squats and bench presses with loads ranging from 20kg to 85% of the participants’ 1RM. The data from TEN were compared to that of the T-Force Dynamic Measurement System (LPT). Reported $r$ values for the TEN (taken as the square root of the $R^2$ values from the reported regression equations) (MV= 0.98, PV=0.96) were slightly higher than those found from this investigation (MV= 0.83-0.96, PV= 0.90-0.94). By visually inspecting the author’s data, mean and peak bench press velocities ranged from approximately 0.20-1.25 m s$^{-1}$ and 0.25-2.25 m s$^{-1}$, respectively. The differences in $r$ values between investigations may stem from the fixed barbell path (i.e. Smith Machine) in Garnacho et al.’s investigation, which would differ from the curvilinear barbell trajectory during a free-weight exercise as used in this thesis. Similarly, Goldsmith [23] reported that the TEN was a valid tool to monitor MV in ranges from 0.09-0.85 m s$^{-1}$ by comparing to that of a 3D motion capture system, but contradicted findings from this study by concluding that it was not valid for PV ranging from 0.29-1.54 m s$^{-1}$. The different conclusions drawn by Goldsmith [23] may have been due to the statistical methods used as the average error in PV (or bias) for TEN was greater in this investigation (0.02-0.2 m s$^{-1}$ versus 0.07 m s$^{-1}$). Due to the large number of data points for Goldsmith’s investigation (522 MV and 553 PV data points with motion capture and 573 MV and PV data points for TEN) and the use of an independent samples t-test, this small average difference may have been statistically significant. However, performing this analysis with a traditional hypothesis test only provides the probability that the velocity values produced by TEN and the motion capture system are not different. It does not tell anything about the strength of the linear associations between the two devices or if the measurement differences are practically meaningful. Any
two devices that use slightly different processing procedures or different transducer/sensor technology would be expected to derive dissimilar velocities, and thus a standard hypothesis testing procedure may find a difference between devices if enough data is collected [123, 124].

The PSH findings from this study differ from those of Banyard et al. [19], Balsalobre-Fernandez et al. [18] and Sato et al. [21]. Although Banyard et al. [19] similarly concluded that the PSH was not a valid tool to measure MV or PV, this was based on the coefficient of variation exceeding 10% rather than the $r$ values being lower than their threshold (0.7). The $r$ values for MV and PV, reported to be 0.93 and 0.91, respectively, were for a free-weight back squat. Balsalobre-Fernandez et al. evaluated the validity of the PUSH device in relation to a T-Force LPT during fixed-barbell path back squats with loads ranging from 25-85% of their 1RM [18]. The authors reported $r$ values of 0.85 and 0.91 for MV and PV, respectively. Assessing the findings qualitatively shows that peak velocity ranged from approximately $0.80 \text{m s}^{-1}$-$2.20 \text{m s}^{-1}$. Investigating a dumbbell overhead press and a dumbbell biceps curl, Sato et al. [21] reported $r$ values ranging from 0.86-0.88 for MV and 0.80-0.92 for PV. In this thesis, $r$ values for PSH ranged from 0.62 in the $0.80 \leq \text{MV} > 0.40 \text{m s}^{-1}$ bin to -0.65 in the $\text{MV} > 1.2 \text{m s}^{-1}$ bin. For PV, $r$ values ranged from 0.52 in the $1.20 \leq \text{PV} > 0.60 \text{m s}^{-1}$ bin to 0.36 in the $\text{PV} > 1.8 \text{m s}^{-1}$ bin. The discrepancy between $r$ values from this thesis and those of Banyard et al. [19], Balsalobre-Fernandez et al. [18] Sato et al. [21], may have been due to factors such as the actual movement velocities attained, the use of free-weights versus a fixed-path, and the actual exercises being tested. Since PSH uses proprietary algorithms to compute barbell velocity with an IMU attached to the forearm, the algorithms for assessing barbell bench press velocity may not be as robust as those assessing the velocity of a barbell back squat. This hypothesis seems to be supported by findings from Orange et al. [22], who compared the validity of PSH to GYM. In their investigation, twenty-nine professional male youth rugby league players performed three consecutive repetitions with 20, 40, 60 and 80%1RM for both a back squat and a bench press. Based on their validity criteria of a Pearson $r$ value of <0.5 as poor, 0.50-0.74 as moderate, 0.75-0.89 as good, and $\geq 0.9$ as excellent, PSH was found to be “good” at monitoring mean velocity at 20, 60, and 80%1RM, and peak velocity at 20 and 80%1RM for the back squat. However, for the bench press it was only found to be “good” at monitoring mean velocity at 40%1RM ($r=0.84$, CI= 0.68-0.92). Although the analysis was based on the load lifted and there is no information about the actual movement velocities attained, the results for the bench press are similar to those presented in this thesis, and demonstrates that PSH may be better suited for monitoring back squat velocity than bench press velocity. Orange et al. also found that PSH demonstrated the poorest validity (i.e. lowest Pearson $r$ values) during the bench press at 20 and 80%1RM. Assuming this would correspond to the maximum and minimal velocities that they would have tested, their results also match those of this study in that the PSH performed the poorest in the fastest and slowest mean and peak velocity bins.

It is also important to note the differences between the two types of devices (i.e. LPT vs IMU) and their ability to accurately assess MV and PV. In this investigation, the LPTs were found to be valid across almost all MV bins and PV bins, whereas the IMU was not. The LPTs and IMUs tended to overestimate or underestimate velocities depending on the actual movement velocity (Table 3.0.2 and Table 3.0.3). These discrepancies between classes of devices may stem from different computational approaches to estimate velocity (i.e. measuring displacement with an optical rotary encoder and calculating the derivative versus measuring accelerations of the forearm and integrating to calculate velocity).
Figure 3.0.2: Distribution of errors for the Tendo (red), GymAware (green), and PUSH (blue) when computing mean velocity in comparison to a 3D motion capture system. White diamonds represent the average error (bias). Black horizontal lines represent the median error value. The bottom and top of the boxes represent the 25th and 75th percentile, respectively. The distance between the top and bottom of the box represents the interquartile range (IQR). Whiskers represent the largest error score present in the data that is less than 1.5x the IQR. Black dots represent error scores beyond the whiskers.
The smaller $r$ values, larger relative error relative to the motion capture velocity, and overestimation in MV for GYM and TEN across all bins may have been a result of excess tether unwinding. As the barbell is lifted, a tether anchored to the barbell and attached to a spool in the LPT unwinds. As the lifting phase of a repetition ends, the barbell decelerates. During this deceleration of the barbell, the angular momentum of the spool may cause it to keep rotating at a rate disproportional to the barbell’s current velocity. Therefore, excess tether may unwind and erroneously record a greater displacement of the barbell, or compute a greater movement velocity, than what occurred. Additionally, it would be expected that when lifting at faster velocities, the spool would have a greater angular momentum and would therefore overestimate MV even more, which is what was found in this investigation. Furthermore, because this type of error would only be expected during the barbell’s deceleration, PV would not be affected by this limitation. Indeed, the $r$ value, average relative error, and bias did not improve as peak velocity decreased.

Similar to the LPTs, the barbell’s movement velocity influenced the validity of PSH. Although not valid in any MV or PV bin, there was a performance decrement at either end of the velocity spectrum (i.e. $MV \leq 0.4\,m\,s^{-1}$ and $MV > 1.2\,m\,s^{-1}$, $PV \leq 0.6\,m\,s^{-1}$ and $PV > 1.8\,m\,s^{-1}$). Specifically, the average relative errors were much larger in the $MV > 1.2\,m\,s^{-1}$ bin (and a negative correlation with the motion capture was found). PSH also tended to, on average, underestimate MV and PV by $0.86\,m\,s^{-1}$ and $0.89\,m\,s^{-1}$, respectively in the fastest velocity bins. The increased error found at these faster movement velocities may have been a result of the accelerations imparted on the barbell when lifting faster, potentially exceeding the maximum g-force threshold of the device’s hardware. This could occur between the descending and ascending phase during a maximum velocity test with a light load, or during the deceleration phase at the end of a non-ballistic bench press with a light load. If exceeding the tolerable accelerations for the IMU at faster movement velocities, it is possible that the resulting signal to be integrated will be inaccurate, leading to velocity data with large errors relative to the motion capture system. Additionally, at very slow movement velocities, the acceleration of the barbell may be close to $0\,m\,s^{-2}$. When the acceleration of the barbell is this low, the IMU may be more susceptible to the influence of unwanted portions of the measurements (i.e. noise) than the desired portions (i.e. signal). As this signal-to-noise ratio decreases, the calculated velocity may be more prone to error as it would not be based primarily on the “true” acceleration of the barbell (signal), but on the disturbances in the electrical signal (noise). The poor validity in the middle MV and PV bins might also be explained by the difficulty for the employed algorithms to derive velocity from the linear and radial accelerations of the forearm.

The findings from this study have important implications for the implementation of VBT programs. If being used to estimate 1RM, a range of loads, and thus a range of velocities will be needed to build a load-velocity regression model [2]. Therefore, it will be important to use a device that has been validated across the relevant spectrum of movement velocities. Based on the data from this study, GYM would be most appropriate to collect MV data as it was found to be valid for MV bins less than $1.2\,m\,s^{-1}$. The TEN was only found to be valid at $MV < 0.8\,m\,s^{-1}$, while the PSH was not found to be valid at all. These GYM and TEN findings are not specific to the bench press, however it is important to consider the range of motion of the exercise when extrapolating these results to other exercises. For example, since the range of motion during a bench press is less than that of a squat, the curvilinear trajectory may influence
Figure 3.0.3: Distribution of errors for the Tendo (red), GymAware (green), and PUSH (blue) when computing peak velocity in comparison to a 3D motion capture system. White diamonds represent the average error (bias). Black horizontal lines represent the median error value. The bottom and top of the boxes represent the 25th and 75th percentile, respectively. The distance between the top and bottom of the box represents the interquartile range (IQR). Whiskers represent the largest error score present in the data that is less than 1.5x the IQR. Black dots represent error scores beyond the whiskers.
velocity data in the TEN more than it had in this investigation. Since the GYM contains an angle sensor and should therefore not be affected by increased forward-backward displacement, these results may be easier to generalize to any other exercise. Because the PSH device uses proprietary algorithms for each exercise, validity may be limited by the software rather than the hardware. However, because the device performed poorest in the fastest and slowest velocity bins, it may be a hardware problem as well. In this case, results from this thesis could be extrapolated to any exercise in which mean movement velocities are $\leq 0.40\text{m s}^{-1}$ or $>1.2\text{m s}^{-1}$. If using PV to build predictive load-velocity equations, it appears that both GYM or TEN could be used as they were both found to be valid at all PV bins. Again, PSH should not be used for this purpose as it was not found to be valid in any PV bin. Additionally, if providing feedback of movement velocity to encourage athletes to lift quicker, similarly to Randell et al.’s investigation [24], it is important that the metric used for feedback is at best an accurate representation of the performer’s actual movement velocity (valid) and at worse providing a consistent measurement from repetition to repetition (reliable).

When interpreting the results of this thesis, it will also be important to recognize a number of potential limitations. Firstly, there were a limited number of data points in the fastest mean and peak velocity bin. Although the bin ranges were chosen to have a balanced number of data points for subsequent analysis, widening the bin ranges further or utilizing fewer total bins would result in there being less distinction between the fastest and slowest movement velocities. This could mask the validity of the device at extreme ends of the velocity spectrum. Therefore, the bin ranges chosen were to ensure that the number of data points in each bin were as balanced as possible and to ensure that the bin ranges were still able to capture the extreme ends of the velocity spectrum. Secondly, the software and hardware of these devices may have changed since this study was conducted, meaning that the current models of each device may perform differently. Although software and hardware improvements can come quickly, drastic improvements may be more difficult to attain, especially if the computations required to calculate velocity from a device are cumbersome. Although newer devices may perform differently, it is unlikely that major differences would be reported in future investigations for the same device. Third, only a single retroreflective marker was used to model the entire barbell. Although some rotation in the frontal or sagittal plane would be unaccounted for with this method of modelling the barbell, experienced powerlifters were recruited and thus aberrant motion was limited throughout the lifting phase of the bench press. Finally, the TEN device was placed directly beneath the barbell in an effort to minimize forward-backward displacement of the tether during each repetition. While necessary to quantify the validity of the device, this strict standard may be difficult to achieve consistently in a training setting, and thus the findings from this study should be interpreted with this consideration.

3.0.5 Conclusion

The GYM was found to be a valid tool to measure bench press PV and MV when $\leq 1.2\text{ m s}^{-1}$. The TEN was also found to be a valid tool to measure PV and MV if $\leq 0.8\text{ m s}^{-1}$. The PSH was not a valid tool to measure mean or peak velocity in any range based on the criteria used. For the purpose of estimating 1RM, providing velocity-specific feedback, and monitoring fatigue and effort, researchers and exercise professionals should use the GYM. If only concerned with PV data, either the GYM or TEN
could be used interchangeably. The PSH cannot be recommended for use within a VBT program based on the results of this thesis.
Chapter 4

Investigation II
Does the Instruction to Move “As Fast As Possible” Maximize Voluntary Movement Velocity? - Coaching Considerations with Velocity Feedback

4.0.1 Introduction

With the increased popularity of various commercial linear position transducers and inertial measurement units, collecting biomechanical data to assist with making training decisions has become easier for researchers and exercise professionals. For example, barbell velocity data can be quantified with these devices and provide an indication of a performer’s state of readiness. Several researchers have reported a strong association between the absolute velocity attained for a given relative load, making it possible to estimate a performer’s maximum strength [3, 13, 100, 101]. Decreases in intra-set squat and bench press velocity have been highly associated with lactate and ammonia concentrations ($r = 0.95-97$, $p < 0.001$) [107], suggesting that velocity dropoff during a set can provide an indication of the accumulation of metabolic byproducts associated with increased fatigue. Furthermore, given that the velocity attained during a one repetition maximum (1RM) attempt is not statistically different than the velocity attained during the last repetition of a repetition maximum test (xRM) for a given exercise [17], velocity data may help to estimate volitional failure during a training session.

In addition to the potential benefits provided by monitoring velocity while training, how athletes are instructed and provided with feedback can also influence the effectiveness of an exercise intervention. An example of augmented feedback that can be provided to the performer is knowledge of results (KR), which provides information regarding the outcome of their movement [120]. KR can be further divided into qualitative and quantitative KR [125] to suit the intended training objective. While providing quantitative KR, it is also possible to establish specific goals for an athlete to achieve within a training session. It has been suggested that specific goals can provide motivation for people to attain higher levels of performance [27], especially when they are challenging [26]. These specific, challenging goals may motivate people more effectively than an instruction to just “do their best” [26] as this is defined idiosyncratically and does not provide any external or objective reference.

While linear position transducers and inertial measurement units make it possible for training interventions to become data-driven, they also provide an opportunity for researchers and practitioners to provide feedback and instruction to athletes in a new way. Since a combination of both quantitative and qualitative KR could result in superior skill acquisition than only using a single method [120], instructions that utilize velocity data (quantitative KR) may enhance the velocity attained during training. Providing feedback of how fast performers were able to move during a squat jump has been shown to improve vertical and horizontal jump performance, reduce sprint times [24], and decrease the variability in velocity attained between repetitions during training [25]. This may result in athletes attaining higher movement velocities more often during training, which could bring about superior training adaptations. Randell et al. [25] also reported that athletes may attain faster movement velocities during training if provided feedback of their movement velocity. However, it is not known whether the movement velocity attained during a free-weight bench press would be greater if providing athletes with a target velocity (i.e. specific goal) to attain. It is also unknown if the need to supply greater energy while attaining
faster movement velocities may cause an athlete to perform fewer repetitions during future sets of a training session.

Therefore, the purpose of this study was to compare the influence of two instructions on bench press velocity (i.e. move as fast as possible versus achieve a target velocity of 1.0m s\(^{-1}\)). The effects of each instruction on performance in a repetition maximum test were compared to examine the influence of each during future sets of a training session.

### 4.0.2 Methodology

#### Experimental Approach to the Problem

Data from eight powerlifters was collected concurrently with Investigation I, with five more recruited and included solely for this investigation. Participants completed two testing sessions. In Session A, participants were cued to attain a mean velocity of 1.0m s\(^{-1}\) while performing a free-weight bench press with 45% 1RM. In Session B, participants were cued to lift a 45% load as fast as possible. The order of each session was randomized. Participants were required to avoid any 1RM or repetition maximum tests one week prior to their first scheduled testing session. The second session was performed 3-7 days following the completion of the first testing session. Each session involved a general and specific warm-up, a maximum velocity test, a 1RM test, four sub-maximal “velocity” sets, and a repetition maximum test. The maximum velocity test consisted of three sets of one repetition with a wooden dowel. Participants were given a maximum of five attempts to establish their maximum bench press strength. Following the 1RM test, participants performed four sets of five repetitions with 45% 1RM and were provided with the instruction to either attain a target velocity of 1.0m s\(^{-1}\) (Session A) or to move as fast as possible (Session B). Mean and peak velocity of all repetitions were recorded with a three-dimensional motion capture system. In both testing sessions, participants were given feedback regarding their barbell velocity following each repetition. Feedback was provided on a tablet via a GymAware linear position transducer.

#### Participants

Fifteen male powerlifters completed testing, however only thirteen were included for the study (age: 26.8 ± 7.8 years, height: 175.0 ± 6.9cm, mass: 87.2 ± 14.3kg). One excluded powerlifter did not perform both testing sessions within the 3-7-day period, while another self-reported excessive fatigue from the previous session and displayed a 1RM difference of 10kg. The inclusion criteria for the participants was the completion of at least one sanctioned powerlifting competition. The average training experience of the thirteen participants was 7.5 ± 3.9 years and the average years of competition experience was 2.0 ± 0.9 years. This study was approved by the ethics review board of the university. Participants signed an informed consent form and a PAR-Q and YOU form prior to the commencement of testing.

#### Procedures

Participants were given five minutes to perform their own preferred low intensity warm-up and/or flexibility routine prior to the commencement of any bench press exertions. This general warm-up protocol was recorded so that it could be repeated prior to both testing sessions. Following the general warm-up, a series of standardized instructions were provided: 1) the head and hips must remain in contact with the bench and the feet must be kept flat on the floor throughout each repetition; 2) the
barbell must be lowered within 0.05m of the chest, but must not contact the chest; and 3) each repetition must be performed without pausing between the lifting and lower phases. Participants’ grip and foot width were self-determined and marked prior to any repetitions with the barbell for future reference. Both measurements were kept consistent throughout the two testing sessions. If any repetition was disregarded, participants received feedback as to why it did not meet the study criteria. Participants were given five-minutes rest to repeat their attempt during the 1RM test under the given constraints. However, participants were not given an opportunity to repeat any sub-maximal exertions.

After receiving the instructions, a standardized warm-up with the barbell was performed. Participants performed five repetitions with an unloaded barbell (20kg), 35% and 50% of an estimated 1RM. Two-minutes rest was provided between each set. Participants then performed a maximum velocity test with a wooden dowel (approximately 0.26kg) to estimate their maximum velocity (i.e. 0% 1RM). Participants performed three repetitions as fast as possible with the dowel, each separated by 30 seconds of rest. Then, using a protocol similar to Frost et al. [30], participants progressed to a 1RM bench press. Participants performed one set of four repetitions with 60% of an estimated 1RM, one set of three repetitions with 70% of an estimated 1RM, one set of two repetitions with 80% of an estimated 1RM, and one set of one repetition with 90% of an estimated 1RM. Participants were then given a maximum of five attempts to determine their 1RM. Three-minutes rest was provided between each set with loads less than 90% of the estimated 1RM, and five-minutes rest was provided for all sets exceeding 90% of the estimated 1RM.

Following five-minutes rest, participants began their sub-maximal “velocity” sets. In both testing sessions, participants performed 4 sets of 5 single repetitions with 45% of their measured 1RM. Fifteen-seconds and three-minutes rest was provided between each repetition and set, respectfully. During testing Session A, participants were instructed to lift at a mean velocity of 1.0 m s\(^{-1}\) during the lifting phase of the bench press. This velocity was chosen as it represented a velocity slightly higher than that estimated for a 45% 1RM based on load-velocity regression equations from Frost et al. [30] and Helms et al. [16]. Following each repetition, participants were told the barbell velocity. Feedback of barbell velocity was provided with a GymAware linear position transducer attached directly beneath the right collar of the barbell. During testing Session B, participants were instructed to complete the lifting phase as fast as possible. Like testing Session A, participants were told their barbell velocity following each repetition. The order of each session (instruction) was randomized between participants. Following five minutes of rest, participants performed as many repetitions as possible with 75% of their measured 1RM. No instructions or feedback pertaining to the lifting velocity was provided.

Data Collection and Analysis

The mean velocity of each repetition was measured with a three-dimensional motion capture system (Optitrack Flex 13, NaturalPoint Inc., Corvallis, OR, USA). ADTech Motion Analysis Software System (AMASS; C-Motion, MD, US) was used to derive the three-dimensional locations of a spherical retroreflective marker placed on the center of the barbell. Three cameras were placed around the barbell to capture the position of this marker at a sampling frequency of 120Hz. Marker displacement data was smoothed with a 4th order, dual pass Butterworth filter in Visual3D (C-Motion, MD, US) with a cut off-frequency of 10Hz. Event detection algorithms were used to define the bottom and top position of each repetition to isolate the lifting (i.e. concentric) phase. The bottom position of each repetition was
defined as the lowest point of displacement, and the top position of each repetition was defined as the
global maximum point of displacement following the lowest point. Mean lifting velocity was computed
by dividing the displacement by the time between the maximum and minimum events.

Statistical Analysis

The fastest mean velocity attained with a 45% 1RM load during each five-repetition set was the
dependent variable for the first question in this investigation. The fastest mean velocity for each 5-
repetition set was compared with a 2x4 (instruction x set number) repeated-measures analysis of variance.
Mauchly’s test of sphericity was used to ensure equality of variance across all levels of the within-subject
factors. Tukey’s post-hoc test was used to identify any significant differences between factors. Statistical
significance was set at $p < 0.05$. Effect sizes ($\omega^2$) were also computed for significant main effects.

The number of repetitions performed with the 75%1RM load was the dependent variable used to
answer the second question. The instruction used prior to the repetition maximum test constituted the
within-participant factor. To assess the effects of the instruction on a future repetition maximum test,
a Wilcoxon Signed-Rank Test was used to compare the number of repetitions performed in each testing
session. This statistical test was used in lieu of a paired-samples t-test as a Shapiro-Wilk test showed
that the data was not normally distributed ($p = 0.004$). Statistical significance was set at $p < 0.05$. All
statistical analyses were performed with the R programming language.

4.0.3 Results

The average 1RM for participants during session A and B was $140.0 \pm 23.6$kg and $139.0 \pm 23.3$kg,
respectively. Instructing participants to achieve a target velocity prompted a significantly higher mean
velocity ($0.84 \pm 0.10$m s$^{-1}$) in comparison to encouraging them to move as fast as possible ($0.82 \pm
0.09$m s$^{-1}$) ($F = 14.91$, df = 1, 84, $p = 0.0002$, $\omega^2 = 0.29$). The fastest mean velocity achieved during sets
2, 3 and 4 were also found to be significantly higher than set 1, ($F = 10.42$, df = 3, 84, $p < 0.0001$, $\omega^2 =
0.60$; $p = < 0.001 - 0.03$); however, there was no significant interaction effect found ($F = 0.70$, df = 3, 84,
$p = 0.58$). Participant-specific maximum mean velocities were found to be higher ($+0.03 / pm 0.02$m s$^{-1}$)
when asked to achieve a target of $1.0$m s$^{-1}$ in 11 of the 13 participants (Figure 4.0.1). One participant
exceeded this $1.00$m s$^{-1}$ target, with one more exceeding $0.95$m s$^{-1}$ and four more exceeding $0.90$m s$^{-1}$.
There were no differences found in repetition maximum performance between the two testing sessions
($V = 15.5$, $p = 0.43$) (Figure 4.0.2).

4.0.4 Discussion

The purpose of this study was to assess the influence of two velocity-specific instructions during a
free-weight bench press. This investigation also sought to evaluate whether subsequent performance in
a repetition maximum test was impaired to the same extent with both instructions. The results showed
that by providing performers with a challenging and specific target velocity, they were able to attain
faster lifting velocities than when instructed to lift as fast as possible. Furthermore, despite reaching
higher lifting velocities when instructed with a target, subsequent performance in a repetition maximum
test was unaffected. This implies that a target may provide benefit acutely while limiting the negative
impact on future sets within the training session.
The way in which athletes are instructed and provided with feedback can influence their kinematics and kinetics during exercise tasks. This has been noted in various other studies that have demonstrated the instruction and feedback provided to athletes can improve their performance and acquisition of motor skills [64, 120, 126]. For example, participants in other studies have been shown to jump higher [64] and produce a greater jump impulse and lower extremity joint moments [126] with an external focus of attention condition (focus on touching specific rings of a Vertec device) relative to an internal focus of attention (focusing on the finger to touch the rings of a Vertec) or a control condition (jumping as high as possible). A target velocity likely helps to facilitate an external focus of attention, which is important for improving performance and learning [127]. Additionally, by providing a challenging training goal, participants were provided context of how their actual movement velocity compared to a standard while receiving knowledge of results from the GymAware. The instruction to move as fast as possible is defined individually [26], and without any context participants may have only focused on beating or maintaining their previously attained velocity while receiving basic KR. However, by providing this external and specific reference with a target velocity, participants may have focused on trying to attain this target and were not limited by their individually defined goal of trying to beat or maintain their previous velocity. Furthermore, this specific velocity was chosen as it would be difficult for powerlifters to achieve with 45% of their 1RM, and it has been reported that specific and challenging goals are important for improving performance [26, 27]. This study demonstrates that using a target velocity may increase movement velocity during training. KR on its own may also provide some benefit to as following the first set, participants moved the barbell faster during subsequent sets, regardless of the instructions used.

Coker [128] conducted a similar study investigating horizontal jump distance when athletes were instructed with 1) no focus (jump as far as possible), 2) internal focus (rapid extension of knees), 3) external far (focus on jumping as close as possible to a cone placed 3m away), and 4) external attainable (jumping as close as possible to a cone placed at their previous best distance). It was found that horizontal displacement was longer when instructed with the attainable target versus all other conditions. Although participants did not jump as far with the “external far” instruction, it may have been that this goal was too challenging, and thus the commitment to the goal may have lapsed [121]. This thesis highlights that it is important for the target provided to the athletes to be attainable. In this investigation, participants moved at 0.84 m s\(^{-1}\) on average when they were given the target velocity instruction with only one participant actually exceeding the velocity target. Although the goal was not attained by most participants, given that they were still moving at 84% of the target velocity they may not have lost motivation to try to attain that actual target, resulting in them moving faster. However, future work could look to use individualized velocity targets that may better accommodate the abilities of each performer. This could potentially bring about even faster movement velocities during training.

Although the athletes increased their bench press velocity when receiving the target velocity instruction, there was no difference in subsequent repetition maximum performance when compared to the as fast as possible condition. It was hypothesized that by increasing movement velocity during each subsequent set, more energy would be needed and thus there would be greater physiological fatigue. However, this was not seen. There may be several factors that influenced this result. For example, it is possible that while greater energy was expended when instructed to attain a target velocity since the
participants moved quicker, this may have brought about a neural potentiation effect [129]. Therefore, any additional fatigue incurred from the increased energy expenditure may have been offset by the subsequent excitation of the nervous system from attaining faster movement velocities. It may have also been that participants were statistically, but not practically faster when provided with the target velocity instruction versus the move as fast as possible instruction. The average difference across all participants was an increase in 0.02m s\(^{-1}\), which may have been too little for any practically meaningful accumulation of fatigue to occur. Additionally, the method of assessing differences in movement velocities may have also resulted in statistically different movement velocities as only the maximum mean velocities of each set were analyzed. However, if all repetitions in a set were considered in the analysis (as with an average mean velocity of the set) there may have been no statistically significant differences. If this were true, then there may not have been an increased accumulation of fatigue if instructed to attain a target velocity.

Velocity feedback alone (quantitative KR) can reduce the between-rep variability in movement velocity during exercise while also potentially increasing movement velocity [24], but providing a challenging target can also bring about superior changes in movement velocity. The increase in velocity in this investigation was found even though both groups received KR following each repetition. Specifically, 11 of 13 participants attained a higher max velocity when instructed to reach a target of 1.0m s\(^{-1}\) (Figure 4.0.1). These 11 participants moved, on average, 0.03m s\(^{-1}\) faster when given the target velocity instruction. Attaining these faster movement velocities is important if trying to prioritize fast movement velocities during training to bring about superior high velocity-specific training adaptations. However, the use of target velocities can also have other implications if using velocity data to estimate 1RM. If a load-velocity regression equation was determined while an athlete was instructed to move as fast as possible [3, 13, 100, 101], it may overestimate an athlete’s maximum strength if they are instructed to lift a load with a velocity target. This may happen as the performer may have achieved a faster movement velocity during testing not because of any change in their state, but due to a change in instruction. For example, using the regression equations for a bench press from Helms et al. [16], a mean velocity of 1.00m s\(^{-1}\) would correspond to 45% 1RM, but a mean velocity of 0.97m s\(^{-1}\) would correspond to 47% 1RM. Although this difference is small, it may still be important to provide the same instructions during testing and training if using velocity data to estimate 1RM depending on how accurate the prediction must be for the exercise professional and their trainee.

There were limitations in this study that should be highlighted to interpret these findings. Firstly, it is important to note the actual movement velocities attained by the participants. While all participants were lifting 45% of their 1RM, there was large variability in the actual movement velocities, with most not reaching the 1.0m s\(^{-1}\) velocity target. This highlights that with a standardized relative load, a universal velocity target may not be appropriate for a group of athletes as it may be too challenging for some to attain. Therefore, individualized velocity targets might elicit a more favorable response, and superior high velocity-specific training adaptations. Future research should consider utilizing velocity targets that are specific to individuals’ capabilities. Additionally, feedback was provided for each repetition, as is done in practice and has been reported in previous research [24, 25]. However, prior work has also shown that providing KR following each trial may not be as effective when learning a new skill as intermittent KR [130, 131]. Although intermittent KR may enhance long-term learning, it may come
at a detriment to acute performance [130]. Therefore, future research should investigate the potential value in instructing athletes with a challenging target velocity and providing intermittent KR. Finally, the average difference in velocity between sessions was $0.02\text{m s}^{-1}$. This small difference may be difficult to detect with some devices, meaning a valid device, such as the GymAware (Investigation I), should be used to monitor velocity and provide feedback during training.

### 4.0.5 Conclusion

The use of a challenging target velocity was able to elicit faster movement velocities in comparison to instructing participants to “move as fast as possible”, without reducing the number of repetitions performed in a subsequent repetition maximum test. Encouraging participants to attain a challenging target velocity during training may be an effective strategy to employ when trying to elicit velocity-specific training adaptations. Future work is needed to investigate the use of relative and absolute velocity targets to personalize the training response of each performer.
Figure 4.0.1: Participants’ averaged mean velocity across the four sets with 45%1RM. Protocol A represents the instruction to attain a target velocity of $1.0 \text{ m s}^{-1}$. Protocol B represents the instruction to move as fast as possible. Eleven of thirteen participants moved faster (as an average of their four sets) when instructed to attain a target velocity of $1.0 \text{ m s}^{-1}$.
Figure 4.0.2: Participants’ repetitions performed during a repetition maximum test with a 75%1RM load following the instruction to attain a target velocity of 1.0m s\(^{-1}\) and to move as fast as possible (AFAP). There was no statistically significant difference in the number of repetitions performed following the administration of each instruction protocol (p=0.43).
Chapter 5

Investigation III
Velocity-Based Training: Exploring the Potential Implications of Training with Absolute Versus Relative Velocities

5.0.1 Introduction

When training to improve maximum strength, loads are typically assigned relative to a performer’s one-repetition maximum (%1RM), or the load that can only be lifted once. However, manipulating training loads in this manner may not accommodate the state of the athlete on a daily basis. Various external factors such as sleep quality and muscle soreness [7–10] can influence a performer’s 1RM, meaning that an absolute load of 100kg may represent a different relative load (i.e. %1RM) on any given day. Methods such as monitoring the the performer’s perceived repetitions in reserve before reaching muscular failure (RPE-RIR) have been used to accommodate fluctuations in a performer’s readiness [99, 132] to avoid consistent maximal strength testing, but it may not be appropriate when when prioritizing faster movement velocities due to the difficulty in gauging RPE-RIR with lighter relative loads [99].

To accommodate the performer’s current state of readiness when faster movement velocities are prioritized, a velocity-based approach may offer unique advantages, particularly given the association between the movement velocity and %1RM when attempting to move as fast as possible (r = 0.89-0.99) [3, 13, 100, 101]. Velocity-Based Training (VBT) traditionally uses a specific absolute velocity (e.g. 1m s\(^{-1}\)) to prescribe loads [2, 3], based on the training adaptation being targeted [119]. There is some evidence to show that this approach may be effective when attempting to increase average power [11, 106], repetition-maximum performance, and peak force and velocity with a 65% 1RM load [106]. Although these findings suggest that absolute velocity targets may contribute to speed and power improvements, they may not accommodate the current state of the performer.

The use of absolute velocities to accommodate to a performer’s current state may not be as appropriate as using a relative velocity. Amongst a group of football players, Caruso et al. (2012) found that the maximum velocity attained during a front squat with loads less than 55% 1RM was not consistent between days (ICC= 0.14, CV= 34.0) [29]. Therefore, an athlete’s maximum velocity may fluctuate daily similarly to maximum strength. Furthermore, and perhaps more importantly, maximum velocity capabilities differ between athletes. For example, unpublished data from our laboratory showed that the peak velocity attained during a bench press with a wooden dowel (approximately 0.26kg) amongst a group of 60 varsity football players was 4.34 ± 0.60m s\(^{-1}\), with values ranging from 3.14-5.72m s\(^{-1}\). These differences in maximum velocity capabilities may be related to modifiable factors such as muscle fibre shortening velocity [72, 73] and coordination, non-modifiable factors such as limb length [119] and muscle attachment points, or the performer’s state of readiness. This potential variation within and between performers highlights the possible limitations of recommending that all members of a group train at the same absolute velocity. Therefore, prescribing absolute velocities to emphasize velocity-specific adaptations may be analogous to prescribing heavy absolute loads to emphasize maximum strength. In either case, this approach would seem inappropriate.

By failing to account for variation in the maximum velocity capabilities within or between performers, the intensity of exercise may not be controlled effectively, especially while prioritizing faster movement velocities during training. To accommodate these differences, and thus regulate training intensity, it may
be more appropriate to assign target velocities relative to the current maximum velocity of the performer. Currently, the variability in performers’ load-velocity profiles and their maximum velocity capabilities has not yet been explored in the literature. Additionally, it is not yet known whether the between-performer variability in training intensity (i.e. relative loads and velocities) is dependent on the absolute velocity target. This can have important implications if using absolute velocity targets during speed and power training (prioritizes higher movement velocities) and maximum strength training (prioritizes higher loads and thus slower movement velocities).

Therefore, the purpose of this study was two-fold: 1) To describe the variability in the load-velocity profiles and maximum velocity capabilities amongst a group of athletes; 2) to determine if the between-athlete variability in training intensity (i.e relative loads and velocities) is dependent on the absolute velocity target.

5.0.2 Methodology

Experimental Approach to the Problem

Mean and peak velocity data from participants’ free-weight bench press trials were analyzed retrospectively from previous work done by Frost et al. [30]. Participants possessed at least 12 months of resistance training experience and could bench press a load equivalent to their body mass. Participants performed a 1RM bench press test, a maximum velocity test, and four bench press repetitions as fast as possible with 6 sub-maximal loads (15, 30, 45, 60, 75, and 90% 1RM).

Question 1:

To assess the variation in load-velocity profiles and maximum velocity capabilities, sub-maximal trials (i.e. 15-90%1RM) were used to create individual load-velocity profiles via linear regression. Descriptive statistics of the two components of these linear regression equations (i.e. the slope and y-intercept), along with participants’ maximum peak velocity attained with a 2.5kg barbell, were used to describe the between-participant variation in load-velocity profiles and maximum velocity capabilities, respectively.

Question 2:

To determine if the variability in training intensity was dependent on the absolute mean velocity target, the average mean velocity of the group for loads ranging from 15-100%1RM was computed. These seven averages were used as “absolute velocities” to simulate a training environment commonly used in the literature and in practice in which athletes would be instructed to attain a specific absolute target velocity. The seven absolute velocities were input into each participant’s linear regression equation to determine their %1RM had they been bench pressing at that absolute velocity target. Additionally, these absolute velocities were expressed as a percentage of each individual’s peak velocity attained with a 2.5kg barbell. The between-participant variation in estimated relative loads and computed relative velocities at each absolute velocity was compared to assess if this variation is dependent on the absolute velocity target used during training.
Participants

Thirty men with at least 12 months of resistance training experience and a 1RM bench press equal to or greater than their body mass volunteered to participate in the study. The participants’ mean ± SD age, height, body mass and resistance training experience were 24.9 ± 4.9 years, 1.79 ± 0.06m, 80.6 ± 9.8kg and 5.6 ± 3.8 years, respectively. Prior to the commencement of testing, all participants read and signed an informed consent and filled out a health questionnaire approved by the Human Ethics Committee of the University.

Procedures

Each participant attended one testing session that involved the completion of a 1RM test and six sets of four single repetitions performed at loads of 15, 30, 45, 60, 75, and 90% of their established 1RM. Participants were permitted to self-select their grip and foot width during the 1RM test; however, the grip width was measured, marked with tape, and maintained throughout the entire session. A closed grip, whereby the fingers were wrapped completely around the barbell, was used for each bench press condition.

The 1RM testing procedure was similar to Doan et al. [133]. Participants were instructed to perform one set of four repetitions at 60% of their estimated 1RM, one set of three repetitions at 70% 1RM, one set of two repetitions at 80%, and one repetition at 90% 1RM. Following these sets, a total of five attempts were given to identify their true 1RM. Three minutes of rest was given between each set. Participants were required to lower the bar to within 0.05m of their chest, but were not allowed to contact their chest with the barbell. Participants were also required to keep their hips and back in contact with the bench and their feet flat on the floor for the entire exertion. All 1RM testing repetitions were completed using a stretch shortening cycle; however, if the barbell contacted the chest or was not lowered within 0.05m of the chest, the repetition was disregarded, and participants were given another three minutes of rest before attempting an additional repetition with the same load.

Prior to beginning the sub-maximal testing protocol, participants were asked to complete two single repetitions as fast as possible with a 2.5kg barbell, separated by one minute of rest, to establish their peak bench press velocity. Following five minutes of rest, four single repetitions were performed as fast as possible at loads of 15, 30, 45, 60, 75, and 90% 1RM. Three minutes and one minute of rest was given between each successive load and repetition, respectively. Loads were lifted in ascending order (i.e. 15%, 30%, 45%, etc.). During each condition, participants were instructed to lower and lift the barbell as fast as possible while ensuring no contact was made with their chest. If the barbell touched the chest, or failed to be lowered within 0.05m of the chest, the repetition was disregarded and repeated after an additional one minute of rest. As with the 1RM testing, participants were required to keep their hips and back in contact with the bench, and their feet flat on the ground at all times.

Data Collection and Analysis

A linear position transducer (PT5A-150, Celesco, Chatsworth, CA, USA) with a signal sensitivity of 0.244 mV/V per millimeter was secured to a wood plank and positioned approximately 1.5m directly
above the center of the barbell. The transducer was zeroed at the start of each repetition as the acquisition software recorded the initial displacement as 0.000 m. The concentric phase of the bench press was initiated at the point of minimum displacement and terminated at the point of maximum displacement. Raw displacement data was smoothed with a fourth order, zero lag, low-pass Butterworth filter with a cutoff frequency of 100Hz. Velocity of the barbell was calculated by differentiating the position-time curve and subsequently smoothed with a low-pass Butterworth filter with a cutoff frequency of 10Hz. The beginning of the lowering phase was described as the first instance of a negative displacement of the barbell, and the end of the lifting phase was described as the point of maximum displacement. Other details of the data analysis process are outlined in Frost et al. [30].

Statistical Analysis

Question 1:

Participants’ mean velocity with each sub-maximal load was computed as the average mean velocity of the four trials for each load (i.e. 15-90% 1RM). Each of these velocities were used to create participant-specific load-velocity profiles by computing linear regression equations. Descriptive statistics (mean, standard deviation, and range) were computed for the two components of this equation (i.e. the slope and the y-intercept) to describe the between-participant variation in load-velocity profiles. Participants’ maximum velocity was defined as the average peak velocity attained during the two repetitions performed with the 2.5kg barbell. The variation in maximum velocity capabilities between participants was also described by computing descriptive statistics.

Question 2:

To assess if the variation in training intensity is dependent on the absolute velocity target, the same individual linear regression equations from Question 1 were used. Seven absolute mean velocities were input into participants’ equations to estimate the corresponding %1RM if they were performing a bench press with that specific mean velocity target. Each absolute mean velocity was also computed as a percentage of each participant’s maximum velocity capabilities (%Vmax). The absolute velocities chosen were based on the mean velocity achieved by the group at each relative load (i.e. 15-100%1RM).

To assess the between-participant variability in estimated %1RM and computed %Vmax, the average estimated %1RM and computed %Vmax of the group was determined at each of the seven absolute velocities. Then, each individual’s absolute deviation from this average was computed (ex. if the group’s average estimated %1RM at 1.0m s\(^{-1}\) was 44%, and an individual’s estimated %1RM at 1.0 m s\(^{-1}\) was 48%, the absolute deviation is 4%). The absolute deviation was used to determine participants’ variability at each absolute velocity target, and were thus the dependent measures for this second question. A repeated-measures analysis of variance was used to determine whether the absolute deviations (i.e. variability) of %1RM and %Vmax were different at the various absolute mean velocities. Mauchly’s test was used to ensure that the variances of all levels of the within-subjects factor (i.e. 7 absolute velocities) were equal. Tukey’s post-hoc test was used to identify significant differences between factors. Statistical significance was set at \(p<0.05\). All statistical analyses were performed with the R programming language.
5.0.3 Results

Question 1:

Participants’ mean 1RM was 105 ± 17kg. There was large variability in the load-velocity profiles and maximum velocity capabilities between participants (Table 5.0.1).

Question 2:

Statistically significant differences were found between the seven absolute velocities for participants’ estimated relative loads (F= 6.24, df= 6, 174, p< 0.001) and computed relative velocities (F=31.87, df= 6, 174, p< 0.001). Tukey’s post-hoc test revealed that the variability in estimated relative loads was significantly greater at the absolute velocity of 1.70m s$^{-1}$ in comparison to all other absolute velocities. No other significant differences were noted. Tukey’s post-hoc test revealed several statistical differences in the variability in relative velocities, with the general trend suggesting that faster absolute velocities yielded greater variability (p< 0.001) (Figure 5.0.1).

Table 5.0.1: Mean, standard deviation (SD), and range of slopes and intercepts from the load-velocity regression equations for each participant. The same descriptive statistics were also used to describe the maximum velocity capabilities of all participants.

<table>
<thead>
<tr>
<th>Slope</th>
<th>Mean</th>
<th>SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1.94</td>
<td>0.21</td>
<td>1.03</td>
</tr>
<tr>
<td>Maximum Velocity (m s$^{-1}$)</td>
<td>4.23</td>
<td>0.68</td>
<td>2.77</td>
</tr>
</tbody>
</table>
Figure 5.0.1: Participants’ estimated relative loads (%1RM) and computed relative velocities (%Vmax) for seven absolute velocities. %1RM was estimated by inputting each absolute velocity into every individual’s load-velocity regression equation. The results from a repeated-measured analysis of variance concluded that there was a significant difference in the variability in %1RM ($p < 0.001$) and %Vmax ($p < 0.001$). Tukey’s post-hoc procedure determined that the variability in relative loads was significantly greater at the absolute velocity of 1.7 ms$^{-1}$ in comparison to all other absolute velocities. Additionally, significant differences in variability were found between 0.10 ms$^{-1}$ and 0.75-1.7 ms$^{-1}$, 0.25 ms$^{-1}$ and 0.75-1.7 ms$^{-1}$, 0.5 ms$^{-1}$ and 1.00-1.70 ms$^{-1}$, 0.75 ms$^{-1}$ and 1.30-1.70 ms$^{-1}$, as well as 1.00 ms$^{-1}$ and 1.70 ms$^{-1}$ ($p < 0.001$).
5.0.4 Discussion

The purpose of this study was two-fold: to examine the variation in load-velocity profiles and maximum velocity capabilities between performers, and to determine whether the variation in performers’ training intensity (i.e. relative loads and velocities) is dependent on the absolute velocity target. Although absolute velocities are frequently used to assign loads when velocity is prioritized during training [11, 106, 119], the findings from this study raise questions. With light loads and thus high velocities, the between-athlete variability was high, which implies that each individual would be using a different relative load (i.e. %1RM) and moving at a different relative velocity (i.e. % VMax), and thus experiencing a difference stimulus during a training session. Since this between-athlete variability was greater at faster movement velocities, there may be greater implications when prioritizing fast movement velocities during training. The larger variation in the relative load and relative velocities that was observed at higher movement velocities was likely due to the different characteristics of each individual’s load-velocity profile and their maximum velocity capabilities. Non-modifiable factors such as anthropometrics [119] (influencing the range of motion of the exercise), and modifiable factors such as muscle fibre type, size and geometry [72, 73, 76] may have contributed to these observed differences. Additionally, it may have also been that slower absolute velocities, which would correspond to heavier relative loads, result in fewer potential coordination strategies between participants to complete the bench press [134]. At faster absolute velocities, which would correspond to lighter relative loads, there may be an increased number of coordination strategies that participants may use. Therefore, the greater variability in training intensity seen at faster movement velocities in this investigation may be a result of the increased variability in movement strategies between participants at faster absolute velocities.

Assigning a single absolute velocity target for a group of athletes may not regulate the training intensity as intended for each individual performer. Using an absolute velocity range (e.g. instructing athletes to attain an absolute velocity of 1.0-1.2m s\(^{-1}\)) may also be inappropriate as the variability in relative loads and relative velocities being used would be even larger than for a single target. Therefore, the recommendations of using velocity ranges for specific training adaptations, provided by Mann et al. [119], should be interpreted with caution, especially if the objective of the exercise session is velocity or tempo-based adaptations. Gonzalez-Badillo et al. [11] examined the efficacy of a training program that assigned loads for youth-aged soccer players based on the load that could be lifted at 1.0m s\(^{-1}\). Although they found this group of players improved their 20m sprint times, vertical jump, and the maximum load they could lift at 1.0m s\(^{-1}\), the data from this thesis suggests it may be more advantageous to based all recommendations on a maximum velocity test conducted at the beginning of the training day. This may serve to provide a participant-specific stimulus, and thus superior velocity-specific training adaptations. However, this training strategy would need to be verified with future research.

If utilizing an absolute target velocity for a group of athletes, these previously mentioned limitations of using absolute velocity targets should be considered, especially when training experienced athletes. In this case, increasingly minor details must be considered to maximize performance both during training and during sport. Therefore, a participant-specific approach, such as using relative velocity targets may be necessary, especially when prioritizing high-velocity adaptations. This is also important when instructing with specific velocity targets to ensure that the target is appropriate, which can bring about faster movement velocities during training (Investigation II). It is recommended that the maximum
velocity of each athlete be tested at the start of each training session and used to establish the velocity to be attained. This can be done with barbell-based exercises, such as back squats, in the gym if using an LPT. This approach could also be taken with other non-barbell based exercises, such as a dumbbell row, if using a valid IMU. By doing so, it would be similar to approaches used by sprint coaches in track and field that base pace strategies on individual athletes’ capabilities, which would be expected to provide superior training adaptations.

There were several limitations with this study that should be noted when interpreting these findings. First, the participants recruited were recreationally trained, meaning it was unlikely that they were experienced with lifting lighter relative loads at fast velocities. Being less familiar with this task, it is possible that some of the increased variability in training intensities reported at faster movement velocities could be accounted for by the participants’ unfamiliarity. Future research could examine this variability in training intensity at various absolute velocities with a population that may be more experienced with lifting lighter relative loads at fast movement velocities during training. Another limitation of this study was that the loading parameters during the load-velocity profile test were not randomized between participants. In addition to heavier loads, increased fatigue can also decrease the number of available coordination strategies for a given task [135]. As the heavier loads during the load-velocity profile test occurred later in the session for all participants, it is possible that the incurred fatigue could have also reduced the number of available coordination strategies. This could explain why smaller variability in training intensity was found at slower absolute velocities. However, given the rest periods provided during this protocol and since participants were not near volitional muscular failure, it would not be expected that participants accumulated the same level as fatigue mentioned in previous studies that have reported decreased movement variability at increased levels of fatigue.

5.0.5 Conclusion

Using faster absolute velocity targets with a group of performers during training would result in greater variation in the relative load being lifted and the relative velocity being achieved. This is due to the variability in participants’ load-velocity profiles and maximum velocity capabilities. If attempting to maximize the athlete’s movement velocities attained during exercise with challenging and specific velocity targets (Investigation II), it may be more appropriate to base this target on the maximal velocity capabilities of the performer rather than using a single absolute velocity target. This may be especially important for experienced athletes that would required increased levels of individualization in their training. Therefore, relative velocity targets, based on the current maximum velocity capabilities of the athlete, should be used during training sessions instead of absolute velocity targets when prioritizing high-velocity specific adaptations.

Although relative velocity targets may be more appropriate for experienced athletes that require additional individualization to maximize their training programs, less experienced athletes that may not require this level of individualization, or athletes trying to build maximum strength (and thus are prioritizing higher relative loads/slower movement velocities), may not require this extra effort in training program design. For experienced athletes, a maximum velocity test can be performed (semi) regularly depending on their experience and the necessity to ensure that any fluctuations in maximum velocity capabilities are captured for that specific session (ex. training sessions following a competition). Despite
this approach being relatively simple to implement, testing performers’ maximum velocity each session may take time away from other important aspects of training, which is why it may be best suited for athletes that require an increased level of individualization.

Basing a velocity target on maximum velocity capabilities also requires a valid instrument to compute movement velocity. Therefore, this approach may be best suited if using LPTs as they tend to be more robust at measuring peak velocity during a maximum velocity test (Investigation I). The use of relative velocity targets should be based on the necessity to accommodate to the individual capabilities of performer, while also taking into consideration the accessibility to valid tools to monitor velocity.
Chapter 6

Summary and Conclusions
The purpose of this thesis was to provide researchers and exercise professionals with evidence-based recommendations regarding the use of velocity data in a training setting. This was done by assessing three things: 1) the validity of three commercially available devices that measure barbell velocity, 2) the influence of instruction on bench press velocity during a training session, and 3) the potential influence of using absolute versus relative velocity targets during training.

A VBT approach requires a device to compute movement velocity while training so that future training decisions can be informed. Although various tools can be used to monitor movement velocity, factors such as cost, portability, and set-up or collection time limit the practical utility of many [18]. LPTs and IMUs have become popular due to their simplicity of use and lower price points relative to other lab-based tools. Based on the findings from Investigation I, GYM is the device best suited for capturing barbell velocity, as it was valid at computing mean velocities up to 1.2 m s\(^{-1}\) and peak velocities >1.8 m s\(^{-1}\). If the target MV exceeds 1.2 m s\(^{-1}\) (as it might for loads below approximately 35\%1RM), it may more appropriate to use a PV target as the LPTs were valid across all PV bins and did not overestimate the movement velocity. However, this also depends on the objective of training, as a mean velocity would provide an indicator of an athlete’s overall movement velocity during an exercise, whereas a peak measure provides only an instantaneous snapshot of what may have occurred and does not tell where the peak occurred. Additionally, it is important to consider that PV data are not as accurate as MV data at estimating 1RM with load-velocity regression equations [3, 100, 101]. Therefore, the use of MV or PV data should be decided based on the purpose of training while also taking into consideration the potential limitations of the tool being used. Furthermore, when using a relative velocity target, it is important to prescribe movement velocities based on the peak velocity attained with a very light load (ex. a wooden dowel), and not the mean velocity. Similar to the previous statement, basing the relative velocity target on the PV attained would ensure that an accurate representation of an athlete’s maximum velocity capabilities is being measured with the commercial tool since the derived MV may overestimate the athlete’s actual capabilities. Additionally, researchers and exercise professionals can use the results from this thesis to inform VBT interventions. If attempting to estimate 1RM [3, 12–15], monitor effort [2, 92, 99], or provide knowledge of results [24, 25], a GYM LPT should be used as it was found to be valid across the widest spectrum of movement velocities. Furthermore, if estimating the proximity to muscular failure during barbell-based exercises via the minimum velocity threshold [2, 17], it is crucial that a device like the GYM is used to ensure that an athlete is training at the desired level of effort.

Although the LPTs tested were found to be valid across all PV bins, and the GYM valid across all MV bins up to 1.2 m s\(^{-1}\), these devices may be limited to primarily barbell-based exercises. Even with barbell-based exercises, their utility may be limited due to the rotational inertia of the spool causing an “overwind” of the attached tether. Therefore, it may be difficult or impossible for these devices to accurately assess the displacement of a barbell traveling faster than 1.2 m s\(^{-1}\). However, an IMU would not be limited by the rotational inertia of a spool and would only be limited by its hardware or software, which is easier to change than the entire design of an instrument. Therefore, as more improvements are made to IMU technology, these devices may have an advantage over LPTs in the future due to the space requirements of the equipment being used, the difficulty with attaching a string to different body segments/implements, and the limited degrees of freedom. This would make using LPTs for other
multi-planar exercises difficult or impossible. Given that velocity specific instruction and feedback can increase movement velocity (Investigation II), it is possible to use this coaching strategy with other multi-planar exercises. For example, medicine ball throws are commonly used to attain velocity-specific training adaptations [136, 137]. While LPTs may not be able to assess the velocity of each throw, IMUs, such as PSH could since they can be worn on the individual and can capture linear, curvilinear, and rotational exercise movements. Therefore, when expanding the ideas of VBT to non-barbell exercises, IMUs may present a unique advantage over LPTs. Given further improvements in IMU technology, they may afford an opportunity to conduct research that assess VBT interventions with non-barbell exercises.

Monitoring movement velocity in an exercise environment may also provide an alternative method to prescribe exercise loads and provide feedback when high movement velocities are prioritized (e.g. speed and power focus). Results from the second investigation demonstrate that providing a challenging velocity target, along with KR, can elicit greater movement velocities than being instructed to move as fast as possible. This is important for maximizing high velocity-specific training adaptations as it ensures athletes are truly moving as fast as possible and are not limited by their self-perceived effort. Previous studies have demonstrated that both the intended and actual movement velocity are important for eliciting velocity-specific training adaptations [38–47, 52, 57]. Additionally, prior training interventions have instructed participants to move as fast as possible [11, 24, 106] with a relatively light external load to ensure they are both providing the intent to move as fast as possible and truly attaining faster movement velocities. However, given the results from Investigation II, challenging target velocities may be a superior way to encourage athletes to move as fast as they physically can. Although just providing velocity feedback, as in the investigation by Randell et al. [25] was shown to decrease the rep-to-rep variability in participants’ movement velocity during a jump squat, participants did not necessarily move faster. Given that the instruction to move as fast as possible may not actually prompt a performer to move as fast as they can, there will be specific instances when “as fast as possible” should not be used as the standard instruction. Instead, using a just-out-of-reach target velocity may bring about faster movement velocities and superior velocity-specific training adaptations. In the investigation by Gonzalez-Badillo et al. [11] investigating the effectiveness of a training program with loads based on athletes’ maximum load they could move at 1.0m s$^{-1}$, no feedback of the movement velocity was provided to the athletes during their training intervention. If challenging velocity targets were provided to the athletes during each training session, the data from Investigation II suggests it may have prompted superior velocities during the exercise session, and thus superior velocity-specific adaptations than they had reported.

Although velocity targets can be a useful strategy while training to elicit a specific response, absolute targets will not be appropriate in every instance approach since they do not accommodate within- and between-performer differences. Investigation III showed that there is greater between-participant variation in the relative loads and relative velocities used if moving at higher absolute velocities. Therefore, at times it would be more advantageous to use challenging (i.e. just-out-of-reach) relative velocity targets to maximize movement velocity and effort. Just as relative loads would be assigned when prioritizing heavy lifts during training, it is more appropriate to assign relative velocities when prioritizing fast movement velocities during training. This will ensure that athletes are moving as fast as possible and that the target itself is based on the capabilities of the individual athlete.
To the author’s knowledge, there has been no research contrasting the training outcomes of a VBT intervention to that of a traditional percentage-load based design or an RPE-RIR based training protocol. Future research that aims to assess the differences in these types of training programs should consider the results from this thesis when designing their VBT interventions. Additionally, exercise professionals should consider these findings when implementing their own VBT interventions. Rather than using absolute velocity targets (instructing athletes to attain $1.0 \text{m s}^{-1}$) to regulate the training loads [11], perhaps the maximum velocity capabilities of the performers should be assessed at the beginning of each session. This can be done with a wooden dowel, or with a lightweight barbell. After obtaining the performer’s maximum velocity, the target mean velocity for the training session can be computed as a relative percentage of the maximum velocity attained on that particular day. By using challenging relative target velocities and instructions that maximizes the movement velocities athletes attain with a given load, training can be regulated on a daily basis. Although absolute velocity targets may be easier to implement with a group, the outlined limitations of this approach may not be suitable for elite level athletes that need more individualization for their exercise regimes. Given the extra refinement required for elite level athletes, the extra work of assessing a maximum velocity at the start of each workout is well justified. Finally, researchers and exercise professionals should use LPT-based devices, such as the GYM, when collecting velocity data and providing feedback to the athletes while using barbell exercises. In doing so, an accurate representation of the athlete’s movement velocity would be captured, thus providing personalized feedback to athletes and facilitating the sharing of results with other professionals. However, with further software and hardware improvements to IMUs that will make them valid at quantifying movement velocity, they would allow researchers and strength and conditioning professionals to expand on VBT to other non-barbell exercises.
Chapter 7

Technical Note
Does the Conditioning Method Influence the Interpretation of Differences in Bench Press Velocity?

7.0.1 Introduction

The integration of technology into the exercise environment has afforded a unique opportunity to compute data such as mean and peak barbell velocity, yet consideration is rarely given to how the data is conditioned. For example, the average velocity of 5 consecutive repetitions (i.e. an entire set), the average velocity of the “middle” repetitions of a single set (i.e. exclude the first and last repetition), the average velocity of the first or last repetition, the maximum or minimum velocity of any repetition, or the range of velocities achieved throughout a single set can each provide valuable insight. However, the conditioning method used could change the interpretation of the data, thus influencing whether an intervention is deemed “effective” or not. Therefore, the purpose of this study was to examine the inter-set differences in mean bench press velocity using seven distinct conditioning methods.

7.0.2 Procedures

Thirteen male powerlifters (26.8 ± 7.8 years old, 87.2 ± 14.3kg, 7.5 ± 3.4 years training) completed two testing sessions within a 7-day period. Participants first performed a standardized warm-up with the barbell, followed by a maximum velocity test in which three repetitions with a wooden dowel (approximately 0.26kg) were performed as fast as possible. Then, participants were given five attempts, with five-minutes rest between each lift, to establish their maximum strength (i.e. 1RM). Following the 1RM test, four sets of five single repetitions were performed with 45%1RM. Participants were instructed to lift the barbell as fast as possible while performing each repetition. Fifteen seconds and three minutes rest were given between repetitions and sets, respectively. All bench-press sets were performed by lowering the barbell to within 5cm of the chest and immediately lifting the barbell until the elbow joint was completely extended. The hips, shoulders, and head remained in contact with the bench at all times while the feet remained flat on the floor. The first and fourth set were assessed for this investigation.

Barbell kinematics were collected by recording the position of one retroreflective marker placed at the center of the barbell with a 3D motion capture system (Optritrack Flex 13, NaturalPoint Inc, OR, USA). Data was smoothed with a 4th order Butterworth low-pass filter. Event detection algorithms were used to determine the minimum and maximum displacement of the barbell during each repetition. Only the ascending phase was analyzed. Data was processed with Visual3D (C-Motion, MD, US). The mean velocity difference between the first and fourth set for each conditioning method was compared using 95% confidence intervals. The conditioning methods used were: 1) mean of 5 repetitions; 2), maximum of 5 repetitions; 3) minimum of 5 repetitions; 4) range of 5 repetitions; 5) mean of middle three repetitions; 6) the first repetition; and 7) the final repetition.

7.0.3 Results

Although the between-set difference for all conditioning methods shared similar polarity, the magnitude of the difference was larger when using the range, minimum, and first repetition (Figure 7.0.1). The width of the 95% confidence intervals suggest that the use of specific conditioning methods would likely
conclude a statistically significant between-set difference at $p < 0.05$ (set average and set maximum), while others would not (Figure 7.0.1).

7.0.4 Conclusion

The data conditioning method used changed the interpretation of between-set differences in the free-weight bench press mean velocity. This implies that the conditioning method would have influenced whether the intervention was deemed “effective” or not. If using velocity data to assign training loads or provide feedback during a training session, exercise professionals and sport scientists should consider using averages of a set and/or the fastest repetition of a given set to detect changes in barbell velocity as these methods demonstrate the lowest variability between sets, thus making them more appropriate to detect changes that may occur.

When assessing whether an performer’s velocity has increased, using the maximum velocity from a set may be most appropriate as it captures the maximum capabilities of the athlete and is not influenced by any other repetitions from the set, as an average measure might be. However, if assessing an performer’s overall capability throughout an entire exercise set, only assessing the maximum velocity attained can mask information about other repetitions. In this case, it may be more appropriate to use an average velocity measure. Using the average of the middle repetitions of the set may be more appropriate for beginner athletes that display greater variability in movement velocities during the first and last repetitions due to the lack of familiarity with a movement or fatigue. For more experienced athletes that demonstrate greater consistency in movement velocity throughout an exercise set, the first and last repetitions could allow other relevant information to be gathered by taking the average velocity of the entire set.
Figure 7.0.1: Average relative difference (%) between set 1 and set 4. Error bars represent the 95% confidence interval (CI). The vertical red line would represent no difference between interventions. CI’s that overlap the red line suggest that no statistical differences would likely be found at $p<0.05$, whereas no overlap would suggest a statistical difference would be found. The average of the set (Set AVG), the average of the set excluding the first and last repetition (Set MidAVG), and the maximum mean velocity of the set (Set Max) appear to have the greatest statistical power for detecting a potential difference. The set’s first repetition (Set First), last repetition (Set Last), minimum velocity (Set Min) and difference between the fastest and slowest repetition (Set Range) all demonstrated large variability, reducing their power to detect a potential difference.
Chapter 8

Supplement- Investigation I
Figure 8.0.1: *Picture of the Tendo (far left) and GymAware (left) attached to the barbell.*
Figure 8.0.2: *Picture of the retroreflective marker setup on the barbell.*
Figure 8.0.3: Picture of the retroreflective markers placed on the wooden dowel used for maximum velocity testing. The Tendo (far left) and GymAware (left) were attached to the right side of the dowel, as they were for the lifts with the barbell.
Figure 8.0.4: Scatter plots of the motion capture mean velocity with the mean velocity recorded by each device.
Figure 8.0.5: Scatter plots of the motion capture peak velocity with the peak velocity recorded by each device.
Figure 8.0.6: *Bland-Altman plots representing the averaged velocity of a mean velocity data point (i.e. summing the motion capture mean velocity with the device mean velocity and dividing by two) and the error associated with each device in comparison to the motion capture. Black horizontal line represents the average error (i.e. bias). Red dotted lines represent ±SDx1.96.*
Figure 8.0.7: Bland-Altman plots representing the averaged velocity of a peak velocity data point (i.e. summing the motion capture peak velocity with the device peak velocity and dividing by two) and the error associated with each device in comparison to the motion capture. Black horizontal line represents the average error (i.e. bias). Red dotted lines represent $\pm SD \times 1.96$. 
Chapter 9

Supplement- Investigation III
Figure 9.0.1: Density plot of participants’ maximum velocity.
Figure 9.0.2: Density plot of participants’ slope of their load-velocity regression equations.
Figure 9.0.3: Density plot of participants’ intercept of their load-velocity regression equations.
Chapter 10

Information and Consent Form
Study Title
Does the Instruction to Move “As fast as Possible” Maximize Voluntary Movement Velocity? - Coaching Considerations with Velocity Feedback.

Background and Study Purpose
Variables such as the frequency, intensity, duration, and type of exercise are commonly manipulated to elicit training adaptations. Prioritizing the tempo of exercises by using velocity feedback may be effective in eliciting speed and power adaptations. However, the way velocity feedback is provided may influence lifting performance, and thus training outcomes. The purpose of this project is to examine the effect of coaching cues on bench press velocity and fatigue. We anticipate that these findings will provide insight on the implications of coaching cues and bench press performance. The protocol has been reviewed and approved by the Office of Research Ethics.

Testing Procedures
As a participant in this study, you will attend two 90-minute laboratory testing sessions, at which time you will be asked to perform several bench press trials. During these trials, you will be performing maximal and submaximal lifts. A research assistant will describe the testing procedures and offer a series of general instructions regarding the bench press trials. The data collected in this study will be recorded with a 3D motion capture system and a PUSH™ accelerometer device.

Risks and Benefits
The activities you will be asked to perform in this study are considered moderately risky for pain- and injury-free powerlifters. It is possible that some participants will experience muscular discomfort or soreness as a result of performing. There are no known direct benefits to you as a participant in this study, but results of this research may provide information that future coaches or athletes may use to enhance adaptations from resistance training.

Confidentiality and Privacy of Information
If you agree to participate, a unique identification code will be assigned to you. Your data will be linked with this code, but your personal information will not be linked with the data. Only the principal investigator will have access to the names of participants and will keep this information locked in his personal filing cabinet for a minimum of 5 years. All de-personalized data will be encrypted and stored for a minimum of 5 years on password-protected storage drives that are locked-up in the Musculoskeletal Biomechanics and Injury Prevention Laboratory (Clara Benson Building, Room 059). You will be allowed to film yourself participating in the study, however, the video file will remain in your possession and will not be used for any analysis in the study.

Participation
You are eligible to participate if you are above the age of 18, pain-free, have not experienced any musculoskeletal pain or known injuries in the previous 6 months, have participated in at least one sanctioned powerlifting competition, and can bench press at least 1.5x your body mass. If you do not meet this criteria, please notify the research assistant as you are ineligible for participation. As a participant in this study, you have the right to refuse to participate and to withdraw at any time without penalty. To do so, indicate this to the investigators by saying: “I no longer wish to participate in this...
study”. Your participation is voluntary; there will be no financial or in-kind compensation provided to you.

Inquiries

If you have any further questions or would like to receive more information about this study, please contact the principal investigator (Dr. David Frost) or the co-investigator (Steven Hirsch). If you have questions about your right as a research participant, please contact the Human Research Ethics Program.
Consent to Participate

By agreeing to participate, I confirm that:

- I have read this information form and understand the potential risks and benefits associated with participation in this study, and
- I have had the opportunity to ask questions about this study and received satisfactory answers to my questions, and
- I am aware that I am permitted to record myself participating in the study if I so desire and that this information will not be used in any analysis, and
- I am aware that I can withdraw from the study without adverse consequences at any time, and
- I agree to participate as a volunteer in this study:

Participant Name
(Please Print)

Participant Signature

Date

Witness Name
(Please Print)

Witness Signature

Date
Chapter 11

Par-Q and You Form
Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

**YES to one or more questions**

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

**NO to all questions**

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- **start becoming much more physically active** — begin slowly and build up gradually. This is the safest and easiest way to go.
- **take part in a fitness appraisal** — this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- If you are not feeling well because of a temporary illness such as a cold or a fever — wait until you feel better; or
- If you are or may be pregnant — talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

**No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.**

**Note:** If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME __________________________________________

SIGNATURE ____________________________________________________________________________

DATE __________________________________________________________________________________

SIGNATURE OF PARENT or GUARDIAN (for participants under the age of majority)

WITNESS ______________________________________________________

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.
Bibliography


[33] Dan Cunningham et al. “Strength and power predictors of sprinting performance in professional rugby players”. In: (2016).


[40] Edward F Coyle et al. “Specificity of power improvements through slow and fast isokinetic training”. In: *Journal of applied physiology* 51.6 (1981), pp. 1437–1442.


