MIKE MCGUIGAN

TESTING AND EVALUATION OF STRENGTH AND POWER

ROUTLEDGE

TESTING AND EVALUATION OF STRENGTH AND POWER

Strength and power are recognised as key components of human health and performance. Therefore, it is vital for exercise scientists and strength and conditioning practitioners to be able to assess these qualities effectively. Testing methods of these components are often presented as standalone chapters in textbooks which provides the reader with an overview of these aspects.

Testing and Evaluation of Strength and Power provides a detailed explanation of testing and evaluation methods for strength and power. The book considers the relationship between the methods of assessment, research on the various approaches to evaluation and how practitioners and researchers can use the information in applied settings. The book provides the reader with a comprehensive overview of methods of strength and power assessment protocols and how they can be used to inform programming.

This integrated approach to assessment of strength and power is recommended reading for students on strength and conditioning course and of vital reading to those on specialised courses on strength and power as well as coaches in the fitness testing and strength and conditioning disciplines.

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TESTING AND EVALUATION OF STRENGTH AND POWER

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PRINCIPLES OF STRENGTH AND POWER TESTING

Strength and Power Testing Background

Researchers, sport scientists and practitioners need a solid understanding of the principles of testing to conduct testing effectively. This foundation will be critical for developing a strength and power assessment battery that provides reliable, valid and useful information. The importance of testing specific strength and power capacities will be established in later chapters. Firstly, the rationale for a particular strength and power test needs to be clearly defined. Assessment of strength and power is conducted for different reasons which include:

- Establishing norms for the population the practitioner is working with. For example, it can be insightful to determine strength and power levels at different stages of development (Argus et al., 2012).
- Assessing the effect of an intervention. Strength and conditioning practitioners can use a variety of different tests to determine changes in strength and power in athletes and clients.
- Assisting with team selection. For example, research has shown differences between starters and non-starters in sport such as rugby league (Baker, 2017).
- Identifying strengths and weaknesses to aid with programme design. This is one of the most important functions of strength and power assessment. The use of strength and power tests for informing training programme design will be discussed in more detail in Chapter 10.
- Screening for health outcomes. Health outcomes have been linked to strength and power, so there is potential to use measures as a screening tool. For example, grip strength has been shown to a simple measure to establish strength in

clinical populations that has strong relationships with health (McGrath et al., 2018; Garcia-Hermoso et al., 2018).

- Establishing baseline for strength and power measures to allow for more effective return to performance protocols.

Deciding on Tests

An important first step in assessment of strength and power is determining which test(s) to use. If one cannot determine a good reason for testing, then serious consideration needs to be given as to why we should assess at all.

The choice of tests depends upon several factors, including:

- Available equipment. Strength and power testing do not necessarily require expensive equipment and technology to be effective. Specific types of equipment and technology that can be used with strength and power assessment will be discussed in subsequent chapters.
- Number of participants/athletes/clients to test.
- How much time is available for testing? This will determine how many tests are appropriate. Consideration should also be given to having a backup plan in case changes to the testing circumstances occur. This could include changes in the time available for testing or equipment failure.
- Needs analysis of the sport/event/client to determine key strength and power capacities.
- Trade-off between benefits of the testing and the associated costs. Researchers and practitioners can conduct a cost–benefit analysis to determine whether the benefits of testing outweigh the costs associated with the testing. Going through this process systematically will allow one to determine the utility of the testing.
- Specificity versus general nature of the test. Some tests can be used to assess a general capacity, such as maximal force production (e.g. isometric mid-thigh pull (IMTP) test), whereas others can measure more specific aspects, such as jumping (e.g. countermovement jump (CMJ) with the associated metrics).

Laboratory Versus Field Testing

Traditionally, exercise science has classified tests as either laboratory or field-based tests (Table 1.1). With the development of more portable technologies to assess strength and power characteristics, this classification has become less clearly defined. For example, use of portable force plates has become widespread. This enables testing that used to be conducted under controlled conditions (e.g. force platforms fixed into the ground) into applied settings such as sports clubs (e.g. portable, lightweight force plates), due to the tester being able to transport the

TABLE 1.1 Classification of laboratory and field-based tests and their advantages and disadvantages

	Laboratory	*Field*
Example	Isokinetic dynamometry	Jump testing with contact mat
Advantages	More controlled environment Increased efficiency of testing Well-suited to individual testing	Increased ecological validity More convenient for participants, particularly when working with athletes and sports Testing can be incorporated into training sessions
Disadvantages	Tests assess a wide range of strength and power qualities (metrics) which can make interpretation difficult	More difficult to control environmental conditions and other factors

equipment relatively easily. Evolution of testing has gone even further, as wearable technologies now allow for assessment of many metrics that previously required expensive equipment. In these scenarios, a trade-off may exist due to the perceived lack of control, but it does present significant advantages in terms of ecological validity. The robustness of testing remains important and practitioners need to know that the data they are collecting are valid and reliable.

Testing Concepts

Several strength and power assessment concepts are fundamental. Having a good understanding of reliability, validity and sensitivity of tests can help practitioners implement more effective assessment batteries with clients and athletes. In addition, possessing a basic knowledge of statistics is important for researchers and practitioners. Understanding simple concepts such as central tendency (mean, median, mode), variability (standard deviation), effect size, z-scores, correlation, and confidence intervals is important for the analysis and interpretation of strength and power results.

Reliability

Reliability of testing is one of the most important concepts to be understood by researchers and practitioners. Several different methods of reliability can be applied when deciding if the tests being used are reliable (Atkinson and Nevill, 1998). Test–retest reliability is a common aspect that is of interest to practitioners and researchers. Two components of measurement error are important in terms of reliability: systematic bias (learning effects, motivation) and random error (biological and mechanical variation) of the test (Atkinson and Nevill, 1998).

The common measures of reliability include intraclass correlation coefficient (ICC), coefficient of variation (CV), typical error (TE), standard error of measurement (SEM) and smallest detectable difference (SDD).

Intraclass Correlation Coefficient

The ICC is often the preferred method for determining reliability. The ICC is commonly used in research to provide a measure of the between-subject variation for a test and is the measure of the ratio of variance between the subjects and total variance. Several different types of ICC are available to researchers, and the method chosen should be reported where appropriate (Atkinson and Nevill, 1998; Weir, 2005).

Coefficient of Variation

The CV can be calculated as CV% = standard deviation (SD)/mean × 100. This method is used to indicate the degree of within-subject variation in a test.

Typical Error

The TE of the test is an important measure for researchers and practitioners. The TE is calculated as the standard deviation of the difference between values divided by the square root of 2 (Hopkins, 2000). Knowing the TE of the test provides the researcher with another way of expressing the error associated with that test.

Standard Error of Measurement

The SEM refers to the measure of the amount of error associated with the test (Weir, 2005). The SEM can be calculated as SD √1 minus the ICC (Atkinson and Nevill, 1998). It is directly related to the CV% which is this value expressed as the percentage of the athletes mean variation. Therefore, it reflects the within athlete variation and calculates the variability of the measure at the individual level.

Smallest Detectable Difference

The SDD is another term used in the literature that refers to the ability of a test to detect the smallest meaningful or practically worthwhile change in performance (Drake et al., 2018). This is sometimes also referred to as the minimum detectable change. This concept is discussed more in the section on sensitivity.

Uses of Reliability

Fundamentally, reliability refers to the repeatability or reproducibility of the test. Researchers and practitioners need to be confident that any changes they are seeing in performance are due to factors other than errors associated with the test. For example, strength and conditioning practitioners need to know that any changes they have seen in response to a training programme are due to adaptations rather than any noise associated with the test. Methods for calculating reliability are often used interchangeably but they will determine different aspects of reliability.

In terms of determining reliability, one approach can be to utilise reliability data from published literature. As reliability is related to the number of measures and the nature of the participants, it is important to factor these into the study design. While this is a good starting point, it is optimal for the researcher/practitioner to determine the reliability of testing in the laboratory, in the applied setting and with the population being tested. For example, reliability of a test may be different in a youth population compared to elite athletes (Nibali et al., 2015b). Ideally, conducting their own in-house reliability study is more useful for researchers and practitioners.

What constitutes a reliable test is a common question posed when using strength and power assessments with different populations. Researchers will often set arbitrary cut-off points such as less than 10% for CV as being acceptable reliability (Stokes, 1995). Guidelines are important, but having measures that are as reliable as possible is most critical. Using an ICC of less than 0.7 is also common in the research literature as indicating that the test has questionable reliability. An ICC less than 0.5 is also mentioned as a cut-off for a repeated test to be reliable (Hopkins, 2000). However, the ICC can be difficult to interpret and needs to be as high as possible. Rather than having thresholds for what constitutes acceptable reliability, researchers and practitioners should look to use tests that are as reliable as possible.

The timeframe over which reliability is established is also important. Test–retest reliability is a common approach where the test is conducted over several days to determine reliability. Ideally, it is useful to know the reliability of the test over the duration of the intervention. However, the reality of establishing this can be somewhat challenging for practitioners. Also, determining within-session reliability is important for quantifying the consistency of performance within the session.

Tests should have both high intrarater (consistent results with repeated testing by the same individual) and interrater (between different individuals conducting the same test) reliability. Using different individuals to conduct the tests requires that interrater reliability be considered. For example, when conducting one repetition maximum (1RM) testing a clear checklist needs to be established to ensure consistency for testing (see Chapter 3). Squat depth is a good example of such a scenario where it is vital that clear and objective criteria are known to all the testers.

Validity

Strength and power tests also need to be valid when used by researchers and practitioners. Fundamentally, validity refers to whether the test measures what it intends to measure. For example, does performing the maximum number of repetitions on an exercise which allows an athlete to achieve 20 repetitions measure muscular power? In this case, the test would be more of a reflection of muscular endurance. This may also depend on the individual. For someone who is particularly weak, a push-up test may indeed reflect their strength rather than muscular endurance. Practitioners need to be sure that the test they are using is measuring the variable of interest.

Several types of validity can be considered by the tester when implementing a testing battery. Content validity is an important factor in testing as it refers to whether a test assesses what it intends to measure. Rather than relying on subjective opinion, utilising rigorous approaches to establish content validity is vital. Of particular importance to practitioners is the concept of ecological validity. This refers to the applicability of the test in a real-world setting. Practitioners should use tests that they can apply in their own setting and which generate useful information.

Validity can also be useful when establishing whether a piece of technology can be used to measure aspects of strength and power. Comparing equipment against a gold standard can help to establish the validity of that technology. For example, a range of devices can be used to measure bar velocity. Comparing the velocities of several devices performed by an athlete will often show different values (Perez-Castilla et al., 2019). This is another way to assist with decision making about which types of technology and equipment to use for strength and power assessment. Determining which measures are valid will also assist decision making on what should be included in a testing battery.

As with reliability, a range of validity statistics are available to researchers. Common methods include correlation and use of Bland-Altman plots.

Correlation

Establishing the relationship between the test of interest with a gold standard measurement is a common method to determine validity. For example, researchers could compare the results from wearable devices for measurement against a gold standard force plate. Pearson product moment correlation coefficients can be used to establish the strength of the relationship between the two methods. Useful criteria can be applied to provide descriptors for the strength of the relationship.

One criteria is to use the following: < 0.3 small, < 0.5 moderate, < 0.7 large, < 0.9 very large and < 1.0 nearly perfect (Hopkins, 2009).

Bland-Altman Plots

Bland-Altman plots provide a useful way to visualise the differences between the variables of interest and the extent of the relationship (Bland and Altman, 1995). The plots can show the degree of difference between tests, and are an excellent way to visualise the amount of agreement.

Sensitivity

It is critical for researchers and practitioners to be aware of whether the tests they are using can detect a real change in performance. This is a vital but often overlooked aspect of testing. Practitioners need to be confident that any changes they see as a result of a training intervention are worthwhile. For example, if an athlete increases their 1RM bench press by 2.5 kg following a four-week training block, does this indicate a real change in their performance? The answer will depend on several different factors, including the reliability and error associated with the test. Taking this approach to analysis of testing results can be informative for both researchers and practitioners. It can also help to establish thresholds that can be used to identify and help guide reporting of the testing data (see Chapter 9). Another approach is to establish the signal-to-noise ratio by looking at the degree of change in the test relative to the TE. It has been suggested that a ratio greater than 1.5 is needed for testing where the change is greater than the noise (Hopkins, 2000).

Is the Change Worthwhile?

Knowing what the smallest worthwhile (or meaningful) change of a test and measure can be calculated in several ways. One method is to calculate the smallest worthwhile change as 0.2 multiplied by the between-test standard deviation (Hopkins et al., 1999). This can be calculated using the following formula:

$$\text{Smallest worthwhile change} = 0.2 \times \text{SD}$$

Thresholds can also be applied to classify change as moderate (0.6), large (0.8) or very large (1.0). Placing the smallest worthwhile change within the context of test–retest reliability is also important. This can help practitioners answer the question of whether a measure is reliable or not. For example, the smallest worthwhile change can be compared to the TE of the test to determine the value of the test. Ideally, the smallest worthwhile change will be greater than the TE of the test.

The smallest real change is another method that practitioners and researchers can consider (Beckerman et al., 2001). The smallest real change can be calculated using the following formula:

$$\text{Smallest real change} = \left(1.96 \times \sqrt{2} \times \text{SD}\right) / \sqrt{N}$$

with N referring to the number of athletes that the SD was measured

Sport scientists and practitioners can use standardised scores for the assessment of strength and power testing. Some examples include:

- *Z*-scores

The *z*-score can be used to compare the individual athletes result against the group average. The *z*-score is calculated as follows:

$$Z\text{-score} = \left(\text{test result} - \text{mean}\right)/\text{SD}$$

They can also be used for determining change for the individual against their baseline results.

$$Z\text{-score} = \left(\text{test result} - \text{baseline result}\right)/\text{SD of baseline}$$

Researchers and practitioners can set thresholds for what constitutes a change worth noting via *z*-scores. For example, a threshold of 1.5 has been suggested for monitoring purposes as an indication that a change (positive or negative) has occurred (Thornton et al., 2019).

- Effect size

Effect size is another statistic that can be used to express the magnitude of changes in test results or differences between groups (Flanagan, 2013). For example, a practitioner may be interested in differences in 1RM results between two squads of athletes. Different methods can be used to calculate effect size. One common method (Cohen's *d*) is to use the following formula:

$$\text{Effect size} = \left(\text{mean group 1} - \text{mean group 2}\right)/\text{SD pooled}$$

Effect size can also be used to assess change in a test result of a group:

$$\text{Effect size} = \left(\text{mean post test} - \text{mean post test}\right)/\text{SD pooled}$$

A scale of measures can be used to help researchers and practitioners interpret the effect size with < 0.2 trivial, < 0.6 small, < 1.2 moderate, < 2.0 large and > 2.0 very large (Hopkins, 2009). Confidence intervals can also be calculated (90% and 95% are most common). Confidence intervals are important as they can indicate if an effect is clear or unclear.

Relationship Between Measures

Often with fitness testing, a battery of tests will be used to assess different components of fitness. When testing strength and power, a similar approach can be used as it is known that a component such as strength consists of several different aspects (Chapter 2). However, a challenge that exists when using a range of tests is that they may in fact be assessing the same measures. This can be the case if variables are strongly related to each other. The approach of less is more can be applied in this scenario. Statistical techniques do exist to allow researchers to assess if there is a high degree of relationship or multicollinearity between variables. However, researchers and practitioners do need to be wary about oversimplifying strength and testing. Just because one test is highly related to another does not mean that there is no value to using multiple tests. As will be discussed in subsequent chapters, a variety of strength and power qualities exist that have important roles in athlete performance. Therefore, simply measuring overall strength may not paint a complete picture of performance and have limitations in terms of the ability to impact exercise programming.

Standardisation of Testing

Strength and power testing needs to be performed under consistent conditions. As much as practically possible, the testing conditions should be standardised for repeated testing sessions. Following these processes will increase the validity and reliability of the test. Therefore, any retesting should be conducted using the same conditions as the original testing. This may present challenges to the practitioner. While it may not be possible to control these factors, the tester needs to be aware of the potential impact they can have on the testing results. Athletes need to be provided with a testing environment that allows them to perform at their best. Several factors need to be considered when standardising the testing sessions.

Time of Day

Many studies have investigated the effects of diurnal variation on strength and power measures. The findings are not consistent, with some studies showing no effect on strength and power (Hatfield et al., 2016) and others indicating that diurnal variation does exist (Teo et al., 2011a; Teo et al., 2011b). It appears that time-of-day effects on power can be offset by taking into account body temperature and ensuring that there is adequate warm-up prior to testing (Taylor et al., 2011; West et al., 2014). Individual differences do exist with the chronotype of the individual potentially playing a role (Rae et al., 2015). Individuals with an evening chronotype will typically perform better on strength and power tests in the evening. To help reduce the impact of any diurnal variation, it is advised to complete any repeat strength and power testing at approximately the same time of day where possible and appropriate warm-ups are completed prior to testing.

Instructions

The types of instructions can have an effect on strength and power measures (Halperin et al., 2016; Porter et al., 2012; Porter et al., 2010; Binboga et al., 2013; McNair et al., 1996). Testers will often provide encouragement during maximal strength and power testing, particularly with athletes. Verbal encouragement has been shown to increase strength and power performance (Binboga et al., 2013; McNair et al., 1996). Therefore, this should be factored in and the type of instructions standardised. Instruction has also been shown to have an impact on specific variables such as rate of force development (RFD) (Maffiuletti et al., 2016; Jaafar and Lajili, 2018). Specifically, using the instruction to perform the test as hard as possible versus as hard and fast as possible on an isometric test can have an effect on the result (Holtermann et al., 2007; Jaafar and Lajili, 2018; Sahaly et al., 2001). Instruction is also critical on drop jump tests where contact time is important (Douglas et al., 2018). Instructing the person to minimise ground contact time versus focusing on maximising the jump height upon landing can play a significant role and has been shown to impact test variables (Phillips and Flanagan, 2015).

Testing should begin with an explanation of the testing procedures to help familiarise the athlete or client with those details. Individual preference for verbal encouragement should also be considered. Ultimately, the testing conditions should allow the athlete/client to perform at their best and reduce the risk of injury. Additional aspects of instructions and their impact on specific strength and power assessments will be discussed in subsequent chapters.

Attentional Focus

In addition to the effect of instruction contributing to differences in results, attentional focus can be an important consideration. For example, research has shown that providing instruction with an external focus results in different results on various jump tests (vertical and broad jump) (Porter et al., 2012; Porter et al., 2010; Wulf and Dufek, 2009) and strength measures (Halperin et al., 2016). Interestingly, swearing has been shown to have a significant effect on strength and power performance, with Stephen and colleagues (2018) demonstrating differences in isometric handgrip strength when swearing. It appears that swearing increases pain tolerance, although the mechanism underlying this is unclear.

Order of Tests

The order of testing needs to be considered when conducting strength and power tests. The tester should consider the impact of one test on another test. Post-activation potentiation (PAP) is a potential confounding factor when performing strength and power testing. For example, performing a maximum strength test could increase performance in a subsequent power test (Suchomel et al., 2016; Crewther et al., 2011). Ideally, these tests could be performed on separate days, but how realistic this is should be factored in. If testing is incorporated as part of a training session, there could be some potential order effects that may impact the results. Another confounding issue is the individual response to PAP or preconditioning. As much as possible, the tester should try to standardise the order and timings of the tests if several are being conducted within a session. Individual differences should be considered, as these play an important role within the context of testing sessions (Nibali et al., 2015a).

Fatigue

Fatigue can become an issue when conducting several tests within a session. Testers should also consider the current fatigue status of clients and athletes when conducting the testing and the impact this may have on the results. Arranging the order of the strength and power tests is an important consideration to minimise the effect that fatigue may have. Recommendations can be made for the order of testing and having the most fatiguing tests performed at the end of the testing session. What is fundamental is considering how previous tests can impact on the subsequent tests. From a research perspective, a case can be made for introducing randomisation of the tests to control for the order effect. Researchers and practitioners need to consider the length of time between testing sessions, prior training before testing and the impact of these factors on the testing results. Mental fatigue and stress should also be taken into account due to their potential impact on testing performance (Halperin et al., 2015).

Environmental Conditions

Ideally, the conditions within the testing session should be controlled and standardised as much as practically possible. Testers should keep records of the conditions and circumstances under which the testing was conducted. Where possible, the temperature and humidity indoors should be consistent from test to test. Music is not a factor that is commonly considered, but research has shown that it does have a potential impact on performance during testing sessions (Halperin et al., 2015; Karageorghis et al., 1996). For example, listening to higher-tempo music has been shown to increase grip strength (Karageorghis et al., 1996).

Nutritional Status

Pretesting conditions, including nutritional intake, supplements and hydration status, could also have a potential impact on testing performance (Savoie et al., 2015; Grgic et al., 2018). The impact of intermittent fasting during periods such as Ramadhan may also have potential impact on strength and power performance (Gueldich et al., 2019). Requiring the athletes to avoid caffeine for a certain period prior to testing is a common approach taken within research due to the well-documented effects of caffeine on force production (Grgic et al., 2018; Warren et al., 2010). A potential way to manage any impact that nutrition could have on performance is to use a pretest screening questionnaire to determine any cofounding variables.

Warm-Up

The type of warm-up needs be considered for testing sessions. Warm-ups should be structured to allow the athlete/client to perform as best as possible on the test. The basic principles of warming up should be followed which includes raising the body temperature, appropriate dynamic stretching, and practicing the test. Essentially, this is to help with reducing the risk of injury and maximising performance. The impact of stretching and dynamic movements on subsequent performance is an important consideration and should be standardised from session to session.

Other Testing Considerations

An important part of the testing process is to identify for the athlete, client and/or coach the reason for conducting the testing. Researchers and practitioners should appreciate the learning effect associated with each test and reduce the systematic bias. This will dictate how many familiarisation sessions are required. The number of sessions will depend on the type of test but, at minimum, having one familiarisation session is a general rule of thumb for strength and power tests. Certain tests, such as the vertical jump, may require less familiarisation (Nibali et al., 2015b).

Communication skills are critical when conducting testing. The skills required for managing a group of athletes are important for practitioners to develop. This becomes particularly valuable when testing is set up as a series of stations and the flow of athletes throughout a session will be a consideration. In these scenarios planning will be needed to factor in aspects such as timing between tests and explanations about each individual test. Effective communication will help to create an efficient testing environment, in addition to increasing buy-in from athletes/clients and other support staff. Preplanning and preparing well for the testing session with simple things such as having a list of athlete/client names can be useful.

A simple model that can be used when communicating testing to clients and athletes is what/why/how.

1. What = description of the test and what it will achieve.
2. Why = reason for completing the test and why it is important. For example, the information is being used to make decisions about the training programme.
3. How = description and demonstration of how the test will be performed.

Preparation for the testing sessions is vital. Conducting some type of pilot testing or practice of the testing can help to identify the timings and any potential issues that may arise. This can also help with the set up of the testing. Having to perform multiple tests can be challenging, particularly when managing a group of athletes. Scenarios such as these highlights the importance of being well prepared. The tester will need to factor into timings and order of when the testing should occur. The pilot testing will help to identify these logistical issues and ensure that the testing runs more smoothly. When conducting multiple tests with larger groups of athletes, the tester needs to be adept at managing these aspects. Being able to provide clear instruction, troubleshoot any issues and ensure good flow between the stations will all contribute to a more effective testing environment. Developing these aspects requires experience, so the more practice that testers can get in running these scenarios is useful. An advantage for conducting pilot testing is it also provides an opportunity for familiarisation for the participants.

Rest periods between test efforts and different tests should be considered. Procedures for the different tests will be discussed in subsequent chapters. The logistics of testing large squads of athletes can make the timings of these rest periods difficult to adhere to. Therefore, it is critical to control this as much as possible to ensure it remains consistent. Longer rest periods (3 to 5 minutes) are often recommended for strength and power tests. However, research suggests that for some tests (including 1RM) this length of time may not be necessary (Matuszak et al., 2003; Weir et al., 1994). This is another example of where the practitioner needs to weigh the rigor of testing under controlled conditions versus the real work application of the testing environment when working with multiple athletes.

Figure 1.1 shows a summary of critical factors to consider for standardisation of strength and power testing.

What Is Worth Measuring?

One of the significant challenges that is faced in exercise and sports science is deciding what to measure with testing. Many of the tests outlined in subsequent chapters produce several metrics, which can be overwhelming for deciding which

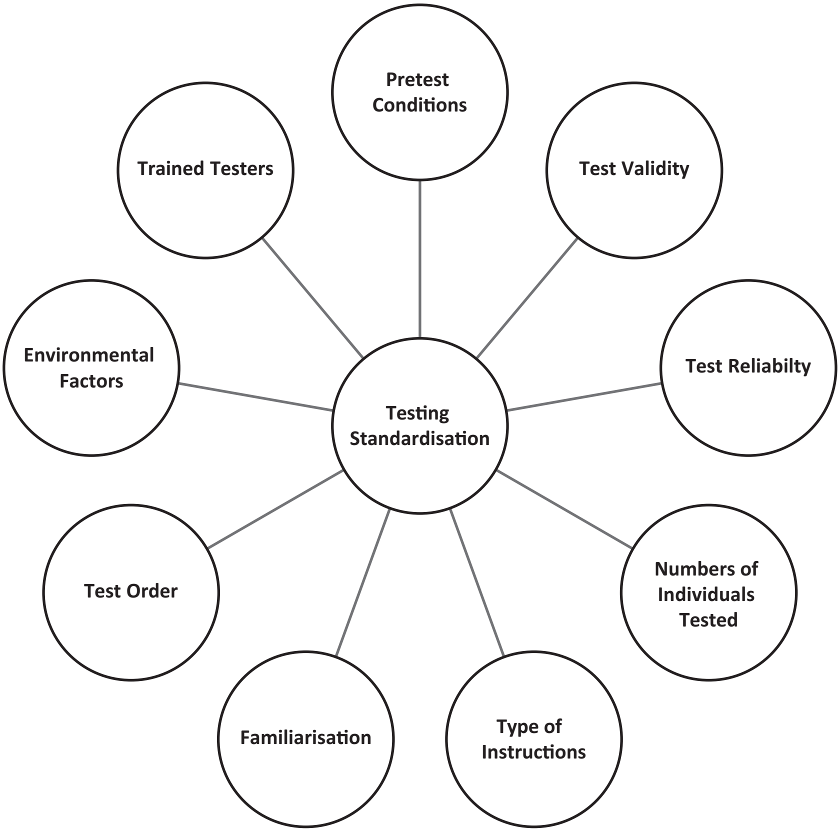

FIGURE 1.1 Key factors to consider when testing to increase standardisation

are useful. For example, when performing a jump test on a force plate, the subsequent analysis may produce more than 20 variables. Obviously, there is no need to report of all these measures, particularly to the client or athlete. Processes that can be followed for informing decision making regarding which variables to report are discussed in the subsequent chapters.

Some key aspects to consider include:

- Relationship of the metric to performance (validity). This can be difficult to determine with team sports compared to individual sports (e.g. weightlifting and powerlifting) where it is clear what the key measures are. For pure strength sports 1RM will be the fundamental test that underlies performance. The research literature provides a starting point for determining which physical capacities underlie performance in team sports.
- Reliability of the variable.

- How easily the metric is understood by the end users. Metrics that are easily understood and are perceived to be important will be more impactful.
- Ability of the measure to have an impact of programming and make the athlete/client better.
- The needs of the sport and individual. A simple needs analysis of the sport can help the tester identify the relative importance of these physical qualities. This can assist with the decision making with which tests to include and which to discard. Discussions with the coach and other members of the support staff also can help to identify which aspects of strength and power need to be assessed.
- Training history of the individual athlete. This factor will determine if the person has previous experience with the test(s) and the amount of familiarisation that is required.

Researchers and practitioners should be mindful of Goodhart's law: "When the measure becomes a target, it ceases to be a good measure". If the focus shifts from the key objective about improving the athlete/client to simply improving test scores, then this may have a detrimental impact. Practitioners may find themselves afflicted with "paralysis by analysis" due to the sheer number of measures that are generated by analysis. Another problematic scenario may be where two equally compelling tests are available and the researcher cannot decide on which one to use. Testing should provide useful information and generate data which can be used to make more informed decisions about programming.

Conclusion

Having a solid understanding of the fundamentals of strength and power testing is important for sport scientists and practitioners. This will allow the tester to ultimately improve the reliability and validity of any tests they use. Fundamentally, this knowledge should allow the tester to determine if any change in a test is worthwhile and how the information can be used to inform practice. Strength and power testing should be standardised to improve its reliability and validity. Practitioners should make informed decisions about which tests and variables are used to ultimately improve the performance of their athletes and clients.

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2

STRENGTH

Strength can be both a simple and complex capacity to assess. At its simplest, strength is a measure of maximum force capability or production (dynamic or isometric). However, it is well established that strength consists of several aspects and depends on the interaction of these factors (Suchomel et al., 2018a; Reya et al., 2019; Vigotsky et al., 2019; Suchomel et al., 2016). Therefore, only capturing a single aspect of strength with testing may miss important components related to performance and health. Strength underpins many aspects of sports performance (Suchomel et al., 2016), in addition to its importance for overall health (Garcia-Hermoso et al., 2018). Figure 2.1 shows a summary of factors that contribute to muscular strength.

Physiological Basis of Strength

Different physiological aspects underlie strength, with force production in the muscles largely dependent on the physiological cross-sectional area which consists of the number of muscle fibres and their cross-sectional area. While the factors will not be discussed in-depth, the key elements will be identified.

Muscle Fibre Type

Muscle fibre type is an important contributor to strength (Fry et al., 2003). Research has demonstrated a strong relationship between Type II fibres and strength (Thorstensson et al., 1977). In particular, Type II fibres have been shown to be strongly related to strength performance (Fry et al., 2003). Studies have shown distinct muscle fibre characteristics of different strength athletes (Andersen and Aagaard, 2010). Interestingly, these findings have not been consistent, with

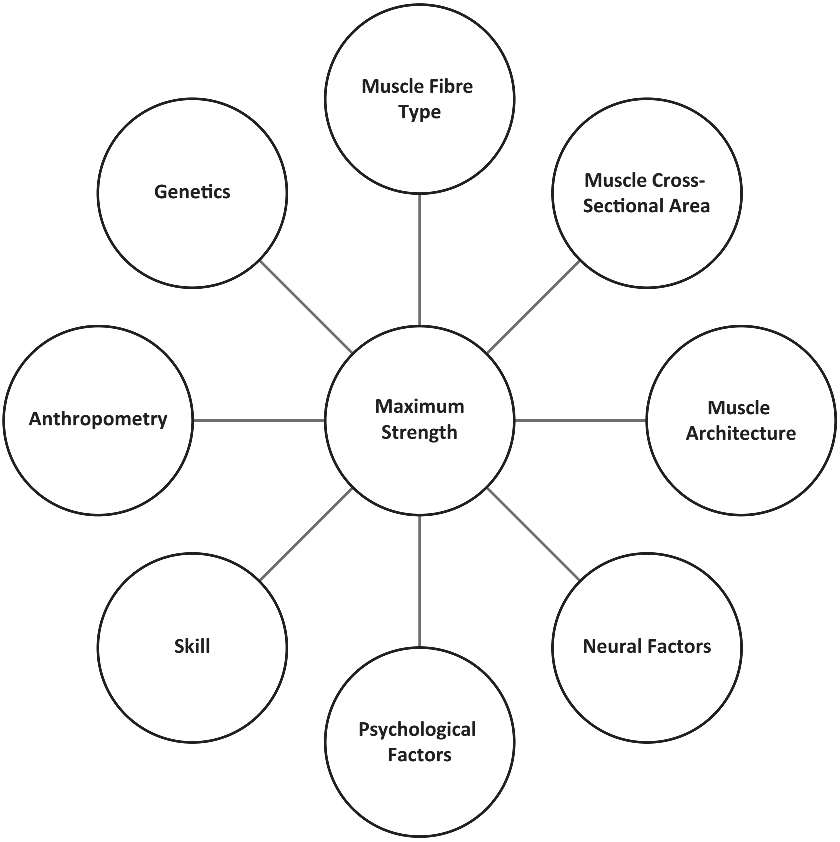

FIGURE 2.1 Summary of factors that determine muscular strength

several notable case studies showing unique profiles within elite athletes (Billeter et al., 2003; Trappe et al., 2015). In general, strength athletes will tend to have a higher proportion of Type II fibres (Andersen and Aagaard, 2010) and a higher ratio of Type II to Type I fibres (Methenitis et al., 2017).

Cross-Sectional Area

Increased cross-sectional area of muscle, particularly Type II fibres, increases force production (Hakkinen and Keskinen, 1989). In general, the greater the skeletal muscle mass, the greater the strength (Ye et al., 2013). Some research has shown a mismatch between changes in muscle cross-sectional area and strength changes, so this is not necessarily a linear relationship (Hakkinen and Keskinen, 1989; Kanehisa et al., 1994). The amount of muscle tissue will be important in determining the degree of actin and myosin cross bridges, as, theoretically, increased area equates to an increased number of contractile elements. It has been suggested that a potential explanation for the lack of consistent findings with relationships between strength and hypertrophy could be due to the different assessment methods that have been used (Vigotsky et al., 2018). Most evidence suggests that cross-sectional area of Type II muscle fibres and the ratio of Type II to Type I muscle fibres are important factors for determining force output (Methenitis et al., 2016; Methenitis et al., 2017). Evidence from studies investigating the effects of detraining, immobilisation and aging attest to the relationship between muscle cross-sectional area and strength (Perkin et al., 2016; Wall et al., 2013).

Muscle Architecture

The arrangement of muscle fibres is an important factor in strength production and potential adaptations (Aagaard et al., 2001; Morales-Artacho et al., 2018; Kawakami et al., 1995). Anatomical cross-sectional area refers to having more sarcomeres in parallel. The pennation angle, which is the angle between the muscle fibres and line between the origin and insertion of the muscle, has been investigated in relation to force production and training adaptations (Aagaard et al., 2001). Other aspects of muscle architecture such as fascicle length have been investigated in relation to strength (Morales-Artacho et al., 2018). The methods used to assess muscle architecture, such as ultrasound, need to be standardised and have high reliability.

Intramuscular Factors

Various factors within skeletal muscle cells play a role in muscular strength and adaptations (Kraemer et al., 2017). For example, intramuscular changes in satellite cells and androgen receptors have been shown to be important in strength (Vingren et al., 2010). These factors are activated acutely with strength training (Vingren et al., 2010).

Musculotendinous Stiffness

Various aspects of stiffness have been studied in relation to muscular strength. For example, studies have investigated the role of musculotendinous stiffness for muscular strength (Wilson et al., 1994). Tendon stiffness refers to the degree of force transmission due to elongation of the tendon. Different methods have been used to measure stiffness (Maloney and Fletcher, 2018). The perturbation method has been used to assess stiffness. Commonly performed jump tests such as drop jumps and bounce jumps have also been used to estimate stiffness (Brazier et al., 2017). Details of these tests are described in more detail in Chapter 7.

Endocrine System

Hormonal contribution to strength is largely dependent on anabolic hormones, including testosterone, growth hormone, catecholamines (epinephrine, norepinephrine, dopamine), cortisol, insulin-like growth factors, estrogen, insulin, and glucagon (Kraemer et al., 2017). The role of hormones and strength has been studied widely (Kraemer et al., 2017; Bosco et al., 2000). The role of these individual hormones, both in the acute and chronic responses for strength, is complex, with a myriad of different hormonal pathways and interactions involved in strength. For example, evidence suggests that testosterone plays an important role in strength (Hooper et al., 2017; Kraemer et al., 2017; Bosco et al., 2000). However, the role of circulating androgens with regards to strength adaptations is debatable, and it appears that this may have less importance than was previously thought (Morton et al., 2016). Effects of androgens on force production appear to be modulated more at the level of the receptor and subsequent intramuscular changes (Vingren et al., 2010).

Menstrual cycle fluctuations in strength have long held interest for researchers (Moore and Barker, 1923; Janse de Jonge et al., 2001; Sarwar et al., 1996). Findings have not been consistent, so it is not clear what changes occur due to large individual differences and variations in types of tests that have been conducted. In addition, limited studies have been conducted in highly trained athletes.

Connective Tissue

The skeletal system is another important contributor to force expression (Hong and Kim, 2018; Nasr et al., 2018). For example, bone has been shown to be important in relation to strength and responds acutely to strength stimuli (Stone, 1988). Connective tissue responses of bone, tendons, ligaments, fascia and cartilage also are vital. Tendon properties are another important factor for strength (Stone, 1988). Strength testing is unable to isolate tissues and their responses and adaptation to training. However, it is important for researchers and practitioners to have a solid working knowledge of these components and their contribution to strength (Stone, 1988). Rather than simply considering skeletal muscle, it is vital to appreciate the different systems that are involved.

Neural Aspects

Nervous system aspects of strength also are important, including motor unit recruitment, firing frequency, synchronisation, rate coding, intermuscular coordination and neuromuscular inhibition (Folland and Williams, 2007). A large body of research has investigated the neural aspects of strength (Folland and Williams, 2007; Balshaw et al., 2018; Balshaw et al., 2017). The nervous system is undoubtedly critical for the expression of strength. Cross education is an interesting phenomenon that has received attention from researchers (Frazer et al., 2018). This occurs when the untrained limb increases strength following a unilateral strength training programme. The underlying mechanisms related to strength are important to understand, particularly when it comes to adaptations that occur.

While neural changes are important during early phase adaptations to training, research has shown that changes within muscle also occur in these initial phases (Staron et al., 1994). This research would indicate that these muscular changes occur acutely as well as chronically. A myriad of neural factors contributes to strength and should be considered with testing. When expressing maximal strength, the ability to utilise the maximum number of motor units (recruitment) will be important. The motor unit refers to the motor neuron and the muscle fibres that it innervates. The firing rate of motor units (also known as rate coding) will also contribute to maximal force production. Synchronisation, which refers to the activation of the motor units, also will be important. Motor unit recruitment during strength tasks has been studied by researchers (Del Vecchio et al., 2019; Van Cutsem et al., 1998). The large type II motor units are particularly important during strength-related movements (Folland and Williams, 2007). Intermuscular coordination has also been suggested as an important contributor to strength (Folland and Williams, 2007).

Psychological Aspects

Physical aspects are critical but psychological factors undoubtedly play a role in maximum force production and should not be ignored (Ikai and Steinhaus, 1961; Tod et al., 2015). Different cognitive strategies have been studied with respect to strength (Tod et al., 2015). Findings are inconsistent but in general support the use of methods such as imagery, goal setting, self-talk and/or psyching-up as methods for enhancing force production (Tod et al., 2015).

Mechanical Factors

Anthropometry

Biomechanical factors play an important role in strength production. Related to this are the anthropometric factors such as body mass, height and segment lengths. An individual's anthropometry will contribute to their capacity to produce force, so this needs to be considered with strength and power testing. Studies suggest that for strength-based sports such as powerlifting and weightlifting anthropometry plays an important role in performance (Keogh et al., 2007; Lovera and Keogh, 2015; Fry et al., 2006; Storey and Smith, 2012; Reya et al., 2019; Cholewa et al., 2019).

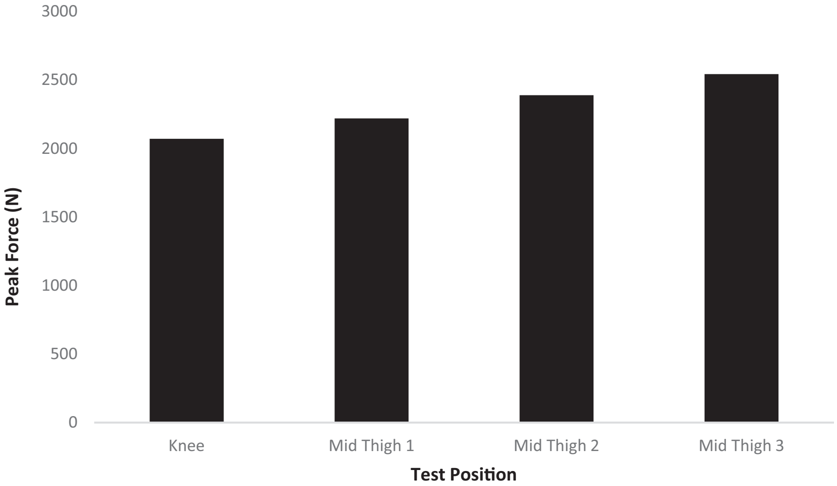

FIGURE 2.2 Relationship between force production and test position during the isometric mid-thigh pull (IMTP) test for an individual athlete

Joint Angle

Strength curves can be used to assess the relationship between force production and body position. This relationship will be determined by the interaction of muscle length and moment arm. The relationship between joint angle and force has important implications for testing, particularly when using isometric tests (Chapter 4). Figure 2.2 shows the relationship for the IMTP test. As can be seen in the figure, the amount of force produced varies depending on the position of the test. While specific joint angles will be recommended for setting up joint angles, the individual's anthropometry will also have an impact on the required setup. Therefore, it is important to standardise testing positions during strength testing, particularly for isometric assessments.

Motor Learning Basis of Strength

Understanding the role of skill acquisition and motor learning is another important area with strength. Traditionally it was believed that initial strength gains in response to a training programme were due to neural adaptations with subsequent changes as a result of changes within muscle, such as increased cross-sectional area (Folland and Williams, 2007). Initial changes have a contribution from improvements due to skill acquisition and motor learning aspects. Intermuscular coordination will also be a contributing factor as movement requires coordination of different muscles (Folland and Williams, 2007). The bilateral deficit, where the sum of unilateral movements is greater than the bilateral movement, should also be considered with strength (Skarabot et al., 2016). The bilateral deficit has been shown to exist in isometric and dynamic contractions (Skarabot et al., 2016). Different mechanisms have been proposed for this phenomenon, such as neuromuscular factors (Skarabot et al., 2016; Jakobi and Chilibeck, 2001). For example, during an isometric squat, individuals will be able to produce more force with single-leg squats combined compared to what they can produce bilaterally (Skarabot et al., 2016). What remains unanswered is how information obtained from the bilateral deficit can be used in programming and the impact of the measure on athlete performance.

Skill development is a critical aspect of testing that is sometimes overlooked. Aspects such as these should be considered when strength assessment is undertaken so that aspects such as learning effects can be accounted for with testing (see Chapter 3).

Genetics

The role of genetics has been studied extensively in relation to strength. For example, candidate genes have been investigated (Eynon et al., 2013; Pickering and Kiely, 2017). Genetics can potentially contribute to the strength ceiling (individual limit for increases in maximum strength) and plays an important role with the different physiological and biomechanical factors that contribute to strength (Suchomel et al., 2018a).

Gender

Differences in absolute strength between genders are often reported in the literature (Hannah et al., 2012; Kanehisa et al., 1994). Findings would suggest that once differences in body size are taken into account that these differences are less pronounced (Kanehisa et al., 1994; Miller et al., 1993; Merrigan et al., 2018; Bishop et al., 1987). Other confounding variables such as training history, movement ability and muscle phenotype could also contribute to reported differences and should be considered (Nimphius et al., 2019).

Strength Terminology

As with most areas in exercise science, different terminology can be used with strength. While this terminology can be confusing, it is vital to understand the different terms and aspects of strength when dissecting the research. For example, strength production is specific to the task performed, with different responses to concentric and eccentric loading (Franchi et al., 2014).

Dynamic Strength

Dynamic strength is the most common component of strength assessment. Dynamic strength and methods such as repetition maximum (RM) testing for assessing this quality are discussed in more detail in Chapter 3. The term isotonic strength is also used when describing dynamic strength. Researchers and practitioners may be interested in measuring strength during both the concentric and eccentric phases of the movement. Concentric only strength would measure the ability to produce force during the concentric phase of the movement.

Absolute Strength

Absolute or maximal strength refers to the total amount of force that can be produced during a specific strength task. It is important to note that this does not have constraints in terms of time. Absolute strength can be measured directly or estimated using submaximal testing (Chapter 3).

Relative Strength

Various methods can be used to express strength in relative terms. For many sports, such as team sports, gymnastics, dance sports, combat sports, jumps and sprints, it is vital to have the necessary levels of relative strength. One of the simplest methods is to express strength relative to body mass (Comfort and Pearson, 2014). Allometric scaling has also been used to account for differences in body size in athletes and other populations (Crewther et al., 2011; Oba et al., 2014; Jaric, 2002; Nygard et al., 2019). A common approach is to express the load lifted divided by the body mass to a power; often two-thirds is used, as this considers the relationship between cross-sectional area and volume. Researchers and practitioners need to understand the rationale for using these approaches (Arandjelovic, 2013; Suchomel et al., 2018b). Certain assumptions need to be met for meeting the necessary criteria to use allometric scaling (Suchomel et al., 2018b; Batterham and George, 1997). The issue of scaling becomes particularly important when dealing with a heterogeneous group.

In strength sports such as weightlifting and powerlifting, scaling methods are used to compare lifters across different weight classes (Vanderburgh and Batterham, 1999; Stone et al., 2005; Sinclair, 1985). Generally, as body mass increases, the level of maximal strength increases (Lietzke, 1956), but this is not a perfect linear relationship (Batterham and George, 1997) (Figure 2.3). Therefore, scaling methods are used in sports to take into account inherent disadvantages larger athletes may have compared to their lighter counterparts when it comes to relative strength (Batterham and George, 1997; Bishop et al., 2018b). In weightlifting the Sinclair formula is commonly used (Sinclair, 1985). In powerlifting, the Wilks formula is used to compare lifters across weight classes and determine the best lifter relative to bodyweight (Vanderburgh and Batterham, 1999). Crewther and colleagues (Crewther et al., 2009; Crewther et al., 2011) used ratio and allometric scaling to normalise strength and power measures obtained from elite rugby union athletes. The findings suggested that allometric scaling may be more

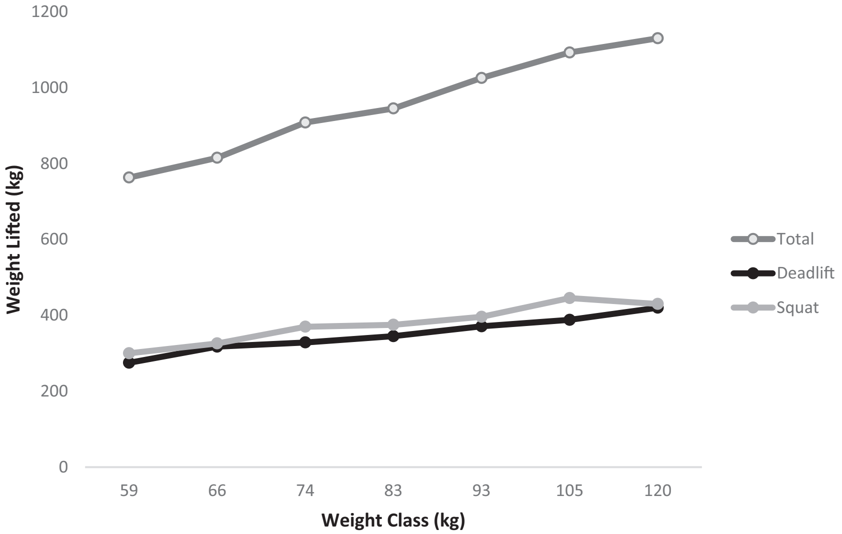

FIGURE 2.3 Powerlifting world record performance data as a function of body mass

appropriate for comparing elite rugby union players of different sizes. However, researchers and practitioners need to be aware of the inherent limitations and assumptions with any model and exercise caution when applying scaling to their strength testing results.

Practitioners will often set benchmarks for certain exercises based on relative measures. Much attention in the literature has been given to certain exercises such as the back squat and bench press. For example, two times bodyweight for the back squat is often mentioned in the literature (Suchomel et al., 2016). The bench press also is regularly discussed as an important exercise (Suchomel et al., 2016). For example, based on data collected on youth soccer players it was recommended that athletes older than 16 years should have a relative back squat ratio of 2.0 (Keiner et al., 2013). It was also recommended that 13 to 15 year olds have a ratio of 1.5 and 11 to 12 year olds a ratio of 0.7. Limitations with expressing these benchmarks relative to bodyweight and child growth and development need to be kept in mind. Guidelines based on progression of eccentric exercise based on relative strength levels have also been made (Suchomel et al., 2019a). Evidence for supporting this argument is often based on cross-sectional studies which show strong relationships between maximum strength and performance (Suchomel et al., 2016). Appropriate scaling methods need to be considered. Whereas strength is a critical aspect of performance and health, this should be placed within the context of the overall training programme. Assessments of the relative importance of strength need to be considered on an individual basis. Regular use of valid and reliable measures of strength will help to accurately determine the importance of strength and track its progress and contribution to the overall training programme (Chapter 10).

How strong is strong enough is often posed in relation the assessment of strength (Stone et al., 2002). Researchers have used different approaches to attempt to answer this fundamental question. While exact recommendations for what represents minimum standards cannot be made, it is generally agreed that strength is a critical component of health and performance (Suchomel et al., 2016). How to best answer these questions depends on several factors. Cross-sectional and longitudinal studies have been conducted on strength levels and athlete performance. For example, cross-sectional studies consistently demonstrate that stronger athletes will perform better in a range of physical tests (Baker, 2017; Stone et al., 2003). Evidence highlights the importance of strength for athletes with relationships between strength and sports specific performance in cycling (Stone et al., 2004), handball (Gorostiaga et al., 2005), rugby union (Cunningham et al., 2018) and weightlifting (Stone et al., 2005). Strength has also been demonstrated to have strong relationships with sport specific qualities such as golf clubhead velocity (Keogh et al., 2009; Wells et al., 2018). While strong relationships exist with important aspects of athlete performance and health, it may be problematic to focus too much on arbitrary levels and targets. It is unlikely that someone can be too strong. Rather the focus should be on the context of strength and if continual improvements lead to better performance and/or health outcomes. Strength should be prioritised if it adds value to the programme but not at the expense of other training aspects. Reliable and valid measures of strength assessment will help to achieve this.

When dealing with youth, it is also important to factor in maturity status, as this has been shown to impact strength (Meylan et al., 2014). Different methods are available to researchers and practitioners for assessing maturity status in children (Mirwald et al., 2002). Chronological age has its limitations for classification children in terms of assessment of strength and power. Biological age will provide a more accurate assessment of the level of development. It is critical to consider the level of development when dealing with children as this has an impact on strength and power. Using anthropometric methods will accurately determine the development level (Mirwald et al., 2002). Prediction equations can be used to assess growth via these methods (Sherar et al., 2005). Having this information is important as it allows practitioners to tease out changes due to training versus those occurring naturally due to growth and development.

Eccentric Strength

Eccentric strength refers to the force associated with the lengthening muscle contraction. While some have concerns about the safety of eccentric strength testing, by following testing procedures carefully this type of testing can provide extremely useful information. Individuals are stronger during an eccentric contraction compared to a concentric contraction. Research would suggest individuals can produce 130–140% more during an eccentric contraction (Douglas et al., 2017b). Eccentric strength has also been shown to be an important but sometimes overlooked component of athlete training programmes (Douglas et al., 2017a; Suchomel et al., 2019b). Eccentric strength assessment is discussed in more detail in Chapter 4.

Isometric Strength

Isometric strength refers to the ability to produce force from a static position. Researchers and practitioners are often interested in maximal isometric strength on a given task such as an isometric squat or mid-thigh pull. Different isometric tasks can be used to assess this aspect of strength. Isometric strength assessment is discussed in more detail in Chapter 5.

Reactive Strength

Reactive strength is another strength component that is of interest to researchers and practitioners. It refers to the ability to change rapidly from eccentric to concentric contraction. It also involves the ability of the musculotendionous system rapidly transitioning from an eccentric to concentric contraction. Reactive strength is a complex capacity that requires a good understanding of the underlying aspects of performance. Maximal strength has been shown to be strongly related to reactive strength (Beattie et al., 2017). Methods of reactive strength assessment will be discussed in more detail in Chapter 7.

Strength Endurance

Strength endurance will be discussed in Chapter 8. It refers to the capacity to perform repeated contractions with a given load or exerting force for an extended period. Many sports require the ability to produce repeated efforts of high-intensity force and power. Therefore, having valid and reliable methods of assessment for this quality is useful for practitioners.

Starting Strength

Starting strength refers to the amount of force that can be produced during the early phase of a movement, often measured within 50 msec. Therefore, this is a component of force production that involves time and will be discussed in more detail in Chapter 7. Table 2.1 shows a summary of the different types of strength.

TABLE 2.1 Different strength qualities

Strength Quality	*Example Assessment*
Maximum strength	One repetition maximum (1RM)
Eccentric strength	Eccentric squat test
Isometric strength	Isometric mid-thigh pull (IMTP)
Strength endurance	Maximum repetitions with 60% 1RM
Reactive strength	Drop jump test
Starting strength	Isometric force produced at 50 msec

Strength Diagnosis

Given that there are several different aspects of strength, it is vital to be able to accurately diagnose them (Newton and Dugan, 2002; Young, 1995). Many different methods of strength testing are available to researchers and practitioners. Using the principles discussed in Chapter 1 will help to inform decision making about the most appropriate test to use. Testing needs to be fit for the purpose, and this is no different when strength testing. Having a clearly defined purpose for the testing will assist with determining the most appropriate test to use. It is important to strike a balance between keeping it simple but not oversimplifying.

Ratios

The ratio of different aspects of strength has long held interest for researchers and practitioners. The ratio of concentric to eccentric strength is often used for assessment of potential imbalances, particularly with isokinetic testing (Bogdanis and Kalapotharakos, 2016). Isometric and dynamic strength have been compared in different ways as a form of strength diagnosis. The dynamic strength deficit (DSD) has been proposed as a useful method for profiling the capacity of individuals to produce force under different conditions (Sheppard et al., 2011; Young et al., 2014) and is discussed further in Chapter 4.

The ratios of various exercises, such as the comparison of pushing versus pulling movements, have also been researched in a variety of populations (Baker and Newton, 2004; Thomas et al., 2015). Another way of looking at this is to measure agonists versus antagonists for assessment of muscle imbalances. As with any measure, an important question is what constitutes an "ideal" ratio. For example, should the push-to-pull ratio be close to 1.0? It is questionable how these ratios relate to injury risk, which is sometimes proposed. Another approach is to use these ratios to help guide training programme design (Chapter 10).

Ratios have also been assessed for measuring asymmetries and establishing potential imbalances. For example, comparing right and left legs during isometric tasks is one approach. This can be achieved using unilateral testing or bilaterally if dual measurement systems are available (Bishop et al., 2018a). It is worthwhile to note that the asymmetries are often test specific and not consistent between different tests (Bishop et al., 2017; Knezevic et al., 2014). In addition, research has shown that the asymmetries also differ depending on the metric that is chosen (Bishop et al., 2019). Tests such as these have been used to measure performance and injury risk in a range of populations (Bishop et al., 2018a). The ratio of unilateral to bilateral performance is another metric that has been studied (McGuigan et al., 2013). The assessment of power will be discussed in more detail in Chapter 6 and applications for programming in Chapter 10.

Importance of Strength

Strength has been shown to be vital for many different populations. Strength has been shown to underpin athletic performance (Suchomel et al., 2016). It is not only athletes that benefit from strength, but a wide range of populations. This is due to strength forming the foundation of power (Suchomel et al., 2016; Douglas et al., 2017b). Strength has also been shown to be related to different components such as change of direction, agility, speed, acceleration, repeat sprint ability, running economy and aerobic endurance (Suchomel et al., 2016; Brady et al., 2019). Strength has also been shown to be important for key performance indicators in team sports such as rugby union (Cunningham et al., 2018; Ross et al., 2015). Strength training forms the foundation of many training programmes, including endurance training (Mujika et al., 2016; Ronnestad and Mujika, 2014). As discussed previously, it can be difficult to determine necessary thresholds for strength required for athlete performance and health. It is only by being able to assess strength accurately that we can begin to make informed decisions about these types of questions. Therefore, researchers and practitioners need to make regular assessments of strength to help inform training programme design.

Strength is a critical aspect for health, with many studies demonstrating its importance for older adults (Mertz et al., 2019; Guizelini et al., 2018; Kraschnewski et al., 2016). Muscular strength has been shown to be strongly related to morbidity and quality of life in older adults (McGrath et al., 2018). Strength can be improved at any age, with even the oldest old obtaining benefits from progressive resistance training (Fiatarone et al., 1990). Strength can also provide benefits in terms of reducing risk of falls and balance. Resistance training as large benefits for bone health in all populations (Hong and Kim, 2018). Developing strength in older people has clear benefits for both longevity and quality of life (Kraschnewski et al., 2016). Adequate strength is also required for completing activities of daily living. It has been suggested that low load-bearing exercise may be insufficient for maximising health benefits in older adults. Therefore, strength training should be an integral part of a daily exercise regimen (Guizelini et al., 2018). Despite this, participation in strength training in this population is low (Kraschnewski et al., 2014). Additional work is needed to translate these findings into practice and encourage even the oldest old to undertake regular strength training.

Youth can also benefit from strength training, with a large body of research showing benefits (Faigenbaum et al., 2016). Strength and power increases, bone health, improved movement competency and psychological benefits are some of the positive outcomes that have been reported following strength training in youth (Faigenbaum et al., 2016). In particular, the health benefits of strength have been highlighted in the literature (Peterson et al., 2016). Youth who develop strength earlier in life have more favourable health outcomes in adulthood. Strength testing and training is able to be performed safely and effectively by children as long as the sessions are properly designed and adequately supervised (Faigenbaum et al., 2016).

Strength is also important in terms of injury prevention (Lauersen et al., 2014; Lauersen et al., 2018; Malone et al., 2018). Resistance training can increase the strength of the underlying connective tissue that may contribute to the decreased risk of injury (Stone, 1988). Assessment of strength can be used during rehabilitation and return to performance for athletes. By establishing preinjury baseline measures for different strength metrics, practitioners may be able to more effectively track athletes during their rehabilitation. This can lead to more informed decisions about when an athlete is ready to return to performance. For example, practitioners may require that the athlete is back to their baseline level of strength prior to returning to performance (Joyce and Lewindon, 2015). It is important to note that strength is only one component of this decision-making process. All measures need to be taken within the context of the overall rehabilitation plan.

While strength is a fundamental aspect of training programmes, it should not be overemphasised at the expense of other aspects. Understanding the contribution of strength to performance and health, the ceiling of development and where it fits in within the overall training plan are important considerations.

Conclusion

Strength is a key aspect of performance and health. Strength consists of several components that need to be considered by researchers and practitioners. Physiological, biomechanical and psychological factors all interact to determine strength capacity. Measures of dynamic, isometric and eccentric strength provide important information across different populations. Strength has been shown to have benefits for many populations. By using effective strength diagnosis, practitioners can more effectively inform decisions regarding training programmes and development of this vital capacity.

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3

TESTING DYNAMIC STRENGTH

Repetition Maximum Testing

Researchers and practitioners need accurate methods for measuring dynamic strength and maximum force capability of athletes and clients. The 1RM test is commonly used to directly measure maximum dynamic strength (Verdijk et al., 2009). The 1RM is a measure of the maximum amount of load lifted according to the correct technical specifications. The 1RM test has consistently been shown to be a reliable test in a range of populations and exercises (Faigenbaum et al., 2012; Seo et al., 2012; Amarante do Nascimento et al., 2013; Comfort and McMahon, 2015; McCurdy et al., 2004; Ryman-Augustsson and Svantesson, 2013; Barbalho et al., 2018; Levinger et al., 2009; Phillips et al., 2004; Ellis et al., 2019; Taylor and Fletcher, 2012; Verdijk et al., 2009; Engel et al., 2019). The reliability of other RM tests has also been established, including 3RM (McCurdy et al., 2004), 5RM (Gail and Kunzell, 2014), 8RM (Taylor and Fletcher, 2012) and 10RM (Jones, 1962). The training level of individuals has been shown to have some impact on the reliability (Ritti-Dias et al., 2011; Benton et al., 2013) and the consistency of dynamic strength performance in competitive athletes (McGuigan and Kane, 2004). Ritti-Dias and colleagues (2011) showed a learning effect across four testing sessions in less experienced trainees compared to no effect in experienced individuals (greater than 2 years of resistance training experience). Comfort and McMahon (2015) demonstrated acceptable reliability for back squat and power clean 1RM in relatively inexperienced (6–12 months) individuals. Barbalho and colleagues (2018) showed excellent reliability for bench press and leg press 1RM testing in elderly women (*n* = 376) before and after a resistance training programme. Therefore, it appears that 1RM testing can produce reliable results in individuals with at least some training base (about 6 months).

The advantages of RM testing are that it provides a direct measure of maximum strength. It can also be used as an effective guide for training programme design. This is due to RM testing being able to estimate other training load zones. Disadvantages of RM testing is that it can be time consuming to conduct, particularly when dealing with large groups of athletes or clients, and when testing multiple exercises. Concerns are sometimes raised about the issue of injury risk, particularly for novice lifters. However, very few adverse events have been reported during maximal strength testing, including older populations (Fiatarone et al., 1990; Frontera et al., 1988). These risks are minimised with adequate supervision by an experienced and qualified tester, along with the individual being tested having some experience with resistance training.

The learning effect associated with 1RM testing does need to be taken into account (Ploutz-Snyder and Giamis, 2001). Some researchers have suggested that due to this reason, it is not an appropriate test for tracking changes in maximal strength (Buckner et al., 2017). While the overwhelming body of research does not necessarily support this, it does raise some important considerations for 1RM testing. Researchers and practitioners should avoid relying on a single measure to capture strength changes in response to a training intervention. Multiple methods of strength assessment may need to be considered to assess dynamic strength.

RM testing is used for several reasons, with the most important being as a guide for programming. Practitioners will often base programming off a percentage of 1RM (e.g. 85% × 5 repetitions) or relative intensity. Alternatively, RM zones can be used for programming. Both approaches have their merits and come down to the individual choice of the practitioner. Research has suggested the using relative intensity results in greater performance and muscular adaptations (Carroll et al., 2018; Carroll et al., 2019). The critical point is that whatever method of programming is implemented, the practitioner needs to use reliable and valid methods of strength assessment.

Theoretically, as the programme progresses the individual will become stronger. Changes can occur quite rapidly, particularly in novice athletes. Research has shown that these changes in dynamic strength can occur within a few sessions (Staron et al., 1994; Stock et al., 2016; Hickson et al., 1994; Hickson, 1980; Zourdos et al., 2016a). For example, Staron and colleagues (1994) showed relative leg press strength increases after only two weeks of resistance training in women. Hickson et al. (1994) found that bench press and back squat strength increased after just one week of heavy resistance training in previously untrained individuals. It is important to note that all participants in the Hickson et al. (1994) study were thoroughly familiarised with 1RM testing prior to commencing the study and high test–retest correlations were reported ($R > 0.95$). This would indicate that the learning effect in this study would have been minimised. Dynamic strength increases to a greater extent in novice trainees but changes are still seen in highly trained athletes (Hakkinen et al., 1987; Zourdos et al., 2016a; Latella et al., 2019). For example, in a series of case studies Zourdos et al. (2016a) showed that highly trained powerlifters could increase 1RM back squat strength within a 10-day period utilising daily 1RM training. Therefore, having methods that can accurately track dynamic strength on a regular basis is vital for both practitioners and researchers.

Factors such as external stress can have an impact of training performance and strength (Bartholomew et al., 2008; Stults-Kolehmainen et al., 2014). For example, Bartholomew and colleagues (2008) showed that college students with lower levels of self-reported stress experienced greater gains in 1RM bench press and squat performance compared to more highly stressed students. What is clear from the research is that many factors can impact on dynamic strength, and that the measures can vary over the days and weeks. Therefore, it is important to have methods available that allow for more continual monitoring of these potential fluctuations.

Estimation Equations

Several methods are available to practitioners and researchers to estimate 1RM without the need to test it directly. These methods work on the relationship between the maximum load that can be lifted relative to the variable of interest. Various equations have been developed for estimating 1RM (Table 3.1). It should be noted that many of these formulas have been developed in practice, rather than from peer-reviewed research. Some of these formulas assume a linear relationship between load and repetitions (e.g. Brzycki, 1993), whereas others assume an exponential relationship (e.g. Mayhew et al., 1992). The Epley formula (Epley, 1985) is an approach that provides a quick and easy method for 1RM estimation. The Brzycki formula (Brzycki, 1993) has also been proposed as a valid method of estimation.

Estimation equations can be useful as a testing method as they allow practitioners to use training as testing (Chapter 10). Monitoring the loads and repetitions in training can therefore be used as a method to tracking strength. This will be more time effective as it removes the need to set aside specific testing periods during the session. It also allows for programming "on the fly" and making regular adjustments to the training programme without the need for regular 1RM testing. Practitioners want to have methods that are practical and easy to use. It is advantageous for practitioners to have methods that can be incorporated as part of the training, rather than relying on standalone testing sessions. However, the practical application of the methods needs to be weighed against the scientific rigour of the methods. In particular, the reliability and validity of these methods need careful consideration to ensure the results from the strength assessment can be used to accurately inform the programming.

Researchers have studied the validity of different equations across a range of populations, including athletes and sedentary groups (Wood et al., 2002; Mann et al., 2012; Reynolds et al., 2006; Mayhew et al., 2008; Mayhew et al., 1995;

LeSeur et al., 1997; Chapman et al., 1998; Whisenant et al., 2003; Knutzen et al., 1999). Many of these studies have compared prediction equations with varying results depending on several factors. The training background of the individual appears to have an effect on the results derived from these equations (Richens and Cleather, 2014; Hoeger et al., 1987; Hoeger et al., 1990; Ware et al., 1995; Braith et al., 1993). For example, more endurance-trained athletes will perform more repetitions at lighter RM loads (Richens and Cleather, 2014). In addition, the relationship between submaximal and maximal strength appears to change with increased training (Braith et al., 1993).

Table 3.1 shows example calculations that show the variation in predicted 1RM with the different formulas. While the choice of equation will have an impact on the result (and many others are available), it does not matter which is used as long it is applied consistently and one is aware of the potential error associated with it. Practitioners should be aware of the differences and limitations of these equations (Mayhew et al., 2008). The variation also differs between different exercises (Wood et al., 2002; LeSeur et al., 1997; Hoeger et al., 1987; Julio et al., 2012). Some error will be associated with tests that rely on prediction, and most research reports that these tend to underestimate 1RM (Wood et al., 2002). Researchers and practitioners should therefore look to use standardised testing methods to ensure the reliability and validity of testing. Even when using robust methods, these estimation equations are still an indirect measure with some error which needs to be recognised.

TABLE 3.1 Common equations used to estimate one repetition maximum (1RM)

Name (Source)	*Prediction Equation for 1RM*	*Example (100 kg × 4 repetitions)*
Brzycki formula (Brzycki, 1993)	load/(1.0278 – 0.0278 × number of repetitions)	109.1 kg
Epley formula (Epley, 1985)	(weight lifted × number of repetitions × 0.0333) + load	113.3 kg
Lander formula (Lander, 1984)	load/(1.013 – 0.0267123 × number of repetitions)	110.4 kg
Lombardi formula (Lombardi, 1989)	load × (number of repetitions$^{0.1}$)	114.9 kg
Mayhew formula (Mayhew et al., 1992)	load/(0.522 + 0.419e$^{-0.055 \times \text{repetitions}}$)	116.5 kg
O'Connor formula (O'Connor et al., 1989)	(load)(1 + (0.025(reps))	110 kg
Tucker formula (Tucker et al., 2006)	1.139 × load + (0.352 × reps) + 0.243	115.6 kg

Source: Adapted from Mayhew et al. (2008).

Other Estimation Methods

Assessing 1RM for every exercise that is used in a training programme can be time consuming. Therefore, approaches where the 1RM can be estimated from another exercise will be of potential interest to practitioners. Potential benchmarks for the ratio of the lifts to each other can be a starting point (Baker and Newton, 2004; Wong del et al., 2013; Wong del et al., 2010; Ebben et al., 2008). This method has been used for both lower body (Ebben et al., 2008; Wong del et al., 2010) and upper body exercises (Wong del et al., 2013). The rationale being that establishing the 1RM for a main lift such as the squat (Ebben et al., 2008; Wong del et al., 2010) or bench press (Wong del et al., 2013) and then using that to estimate the maximal load on auxiliary lifts. Another solution is to establish the 1RM directly for key exercises in the programme and use RM testing for supplementary lifts.

Many other tests have been developed for prediction of 1RM. The majority of these tests require performance of maximum repetitions with a load that can be performed multiple times (Desgorces et al., 2010; Baker, 2004). For example, the modified YMCA bench press test has been used (Kim et al., 2002). A limitation of these tests can be the high number of repetitions that are performed. The popularity of the 225-lb (100-kg) bench press test in the National Football League Combine has led to the development of several prediction methods based on these results (Whisenant et al., 2003; Mann et al., 2015; Chapman et al., 1998; Mann et al., 2012; Mayhew et al., 2002). While these methods can be used to assess and estimate maximal dynamic strength, in stronger individuals they become more a test of muscular endurance. Concepts related to muscular endurance will be discussed in more detail in Chapter 9.

Researchers have also investigated other methods, such as using other strength and anthropometric measures, as an adjunct for maximal dynamic strength estimation (Kanada et al., 2017; Reynolds et al., 2006; Macht et al., 2016). Kanada et al. (2017) estimated 1RM knee extension strength in young men utilising isometric strength and anthropometry. Macht and colleagues (2016) investigated the ability of various anthropometric measures such as arm girth to estimate 1RM bench press performance. The estimated cross-sectional area of the upper arm was shown to provide a relatively accurate estimate of 1RM bench press in 60 physically active men. Researchers have also studied exercises such as pull ups and lateral pulldowns (Halet et al., 2009). The goal of these methods is to provide practitioners with a quick estimate of maximal dynamic strength. While there are advantages to using these approaches, this needs to be balanced with the accuracy of these methods and realizing that they often involve significant error. Therefore, it is preferable to use direct measures for maximal dynamic strength where possible.

Methods for Conducting 1RM Testing

Many methods have been recommended for 1RM testing. Whichever method the researcher or practitioner chooses to use, it is important that the same protocol is used with retesting. An important consideration is the training level of the individual being tested. The 1RM test can be used safely with all populations but it is recommended to only use 1RM testing with individuals experienced with resistance training. A prerequisite is having a minimum of 6 months of training experience and being able to perform correct technique on the exercise being tested. The goal of testing is to find the true maximum in the most efficient manner possible, while reducing the amount of fatigue.

An adequate warm-up should be completed by the lifter. This should include submaximal lifting with the specific exercise using a range of loads. It is also important to have spotters for 1RM testing to ensure safety and help catch the barbell (or dumbells) with any failed attempts on exercises such as squats and bench presses. For weightlifting movements, such as cleans and snatches, lifters would need to be coached on how to fail lifts correctly.

The next step is to have the athlete attempt 50% of their estimated 1RM. It is important to keep in mind that people will often overinflate their estimated strength when self-reporting. Depending on how well the person performs with that load, then it can be increased to approximately 70% of the estimated 1RM. This occurs after a rest period of at least 1 minute between sets.

The technical specifications will vary depending on the exercise. However, it is critical that these are kept consistent for testing. Range of motion of the exercise needs to be considered. Developing a checklist of key technical aspects that need to be achieved and criteria for determining whether the repetition is successful or not is important. For example, in the back squat the depth of the lift needs to be clearly defined and adhered to. In the bench press, the barbell would need to touch the chest and the lift occur through a full range of motion. The tempo of the lift is another important consideration (Headley et al., 2011). For example, Headley and colleagues (2011) showed that 1RM bench press was almost 4% higher when using a moderate versus slow tempo.

The recommendation is often made to rest 3 to 5 minutes between attempts. However, research would suggest rest periods less than this (i.e. 1 minute) are sufficient for most populations (Weir et al., 1994; Matuszak et al., 2003). A general recommendation is to allow the individual enough time that they need to feel adequately recovered.

Testing will continue with attempts close to what is the predicted 1RM. The choice of loads to be attempted at maximum is the most difficult part. Loads need to be chosen that balance the predictive nature of achieving a maximal lift but remaining conservative. It can also be challenging to know how much to progressively increase the load after successful attempts. The final part of the testing comes down to the experience of the researcher or practitioner. At this stage there is an element of trial and error associated with the choice of attempts. The goal should be to find the 1RM within three attempts. Once the number of attempts exceeds this, the athlete will fatigue, and this will impact on the result. Verbal encouragement has been shown to have an effect on 1RM performance, so this should be standardised (Engel et al., 2019).

Considerations for Conducting RM Testing

As with 1RM testing, it is vital that proper technique is maintained on all repetitions. For example, if conducting a 5RM test then all five repetitions need to be performed with correct technique. So, it is important that individuals should be trained and familiar with the correct lifting technique. The same criteria for termination of the test should be used. That is, once adequate technique cannot be maintained then that counts as the number of repetitions completed for that test. Research has shown that as individuals become more fatigued during testing and training, changes in technique can occur (Hooper et al., 2014). In general, tests that use repetitions greater than 10 or loads less than 75–80% of 1RM have been shown to be less accurate (Wood et al., 2002; LeSeur et al., 1997; Chapman et al., 1998; Ware et al., 1995). As the number of repetitions decreases, the more accurate these equations will tend to be.

An important first step is to identify the RM load to be determined. Once this is decided, then similar principles can be applied as for a 1RM test. A warm-up consisting of loads approximately 50–70% of the estimated RM load can be conducted. The protocol is similar as for 1RM testing and the usual consideration needs to be made for safety with spotters on all attempts. Once the warm-up is completed and subsequent submaximal loads finished, a load close to an estimated RM is attempted for the required number of repetitions. The chosen load will need to be estimated so that it is close to the maximum. For example, if attempting a 5RM, then a load should be chosen which would be estimated to allow 4–6 repetitions to be performed. If more than 5 repetitions are completed, then another load should be chosen after an adequate rest period (at least 3 minutes) is taken. Again, as with 1RM testing, a process of trial and error with not many attempts at different loads is required. Otherwise this will lead to fatigue and an underestimation of the true RM.

Velocity-Based Estimation

The increased availability and affordability of devices which can measure velocity has led to development of velocity-based assessment methods (Jovanavic and Flanagan, 2014). This has allowed researchers and practitioners to develop methods that can predict 1RM based on velocity. The load–velocity relationship is well established, with many studies investigating this relationship. It is consistently demonstrated to be a robust relationship, particularly for the bench press (Balsalobre-Fernandez et al., 2018a; Gonzalez-Badillo and Sanchez-Medina, 2010; Jidovtseff et al., 2011; Sanchez-Medina and Gonzalez-Badillo, 2011; Bosquet et al., 2010; Torrejon et al., 2019). The evidence has been less for compelling for other exercises, such as the back squat (Banyard et al., 2017; Carroll et al., 2017; Askow et al., 2019; Martinez-Cava et al., 2018; Sánchez-Medina et al., 2017; Hughes et al., 2018b) and deadlift (Lake et al., 2017; Ruf et al., 2018). It should also be noted that the majority of research showing strong relationships have been conducted using a Smith machine, which provides a more controlled testing environment compared to free weights (Banyard et al., 2017). The extent of the relationship appears to depend on the type of exercise and technique used to perform it (Martinez-Cava et al., 2018). The pull-up exercise has also been investigated and has demonstrated a strong relationship between load and velocity regardless of sex or strength level (Munoz-Lopez et al., 2017). While strong relationships have been demonstrated across a range of exercises and training levels, it is important to remember that this method only provides an estimate of 1RM.

Different approaches have been used to estimate 1RM based on velocity of the lift (Jovanavic and Flanagan, 2014). Velocity can be assessed using some type of measuring device such as a linear position transducer or accelerometer. New technologies have been developed that are more affordable, and therefore perhaps more appealing to researchers and practitioners. Establishing the load–velocity profile for a particular exercise can be used to predict the 1RM (Jovanavic and Flanagan, 2014). However, more research is required across a range of exercises. Lake et al. (2017) investigated the relationship between deadlift 1RM and predicted 1RM using a load–velocity profile (65–90% 1RM). The results suggested that predicted 1RM was less than actual 1RM and that practitioners should exercise caution when using this estimation method for predicting 1RM deadlift. Carroll and colleagues (2017) showed increased variability in maximal concentric velocity with increasing load with the back squat exercise. Other research has also shown that the average concentric velocity varies between exercises and relative loads (Fahs et al., 2019). It appears that the load–velocity relationship differs for individual athletes and exercises, so practitioners should be wary about the interpretation of these relationships (Askow et al., 2019; Hughes et al., 2018a).

The method does allow for ongoing, regular assessment of 1RM which is known to fluctuate. Testing can be done without the need to do maximal testing and, like other prediction methods, can be incorporated as part of the training session. This allows the practitioner to make within session adjustments to exercise intensity. However, the method can be time consuming when testing a large group of athletes.

Method for Estimating 1RM From Velocity

One suggested approach is to use a spectrum of loads with up to 4–5 loads (from 30–90% 1RM) being tested. Generally the more points that are assessed, the stronger and more reliable the relationship (Cuevas-Aburto et al., 2018). However, testing too many loads will increase the time demands which can be problematic when working with large groups of athletes. Some have suggested that it is important to know the 1RM velocity to ensure accuracy of this approach (Jovanavic and Flanagan, 2014). The 1RM velocity is often referred to in the research literature as the minimal velocity threshold (Jovanavic and Flanagan, 2014; Lake et al., 2017). The 1RM velocity across different loads has been shown to be consistent with training (Gonzalez-Badillo and Sanchez-Medina, 2010). It is important to note that this 1RM velocity will vary across exercises (Helms et al., 2017). For example, in powerlifters the 1RM mean velocity has been shown to be 0.23 m/s for the back squat versus 0.10 m/s for the bench press and 0.15 m/s for deadlift (Helms et al., 2017). Sanchez-Medina (2010) showed a 1RM mean velocity of 0.15 m/s for the bench press, and Izquierdo et al. (Izquierdo et al., 2006) found a back squat 1RM mean velocity of approximately 0.30 m/s. For the bench pull exercise, Garcia-Ramos (2019) showed a mean velocity of 0.48 m/s for 1RM. However, the feasibility of this approach can also be difficult when using multiple exercises, particularly if testing a large group of athletes.

Typically, the mean velocity is used for estimating 1RM as it provides a measure of the ability to move the load over the entire concentric phase of the exercise (Jidovtseff et al., 2011). The mean velocity can be calculated as the mean of bar velocities over the concentric phase of the exercise. The mean propulsive velocity refers to the mean bar velocities during the propulsive phase of the exercise where acceleration is greater than acceleration due to gravity. Some research suggests that using mean propulsive velocity is preferable for estimation of relative loads and that predicting 1RM as mean velocity may underestimate 1RM, particularly at lighter loads (Garcia-Ramos et al., 2018b; Gonzalez-Badillo and Sanchez-Medina, 2010; Sanchez-Medina et al., 2010). However, mean velocity has been shown to have greater linearity and be more reliable than mean propulsive velocity during different variations of the bench press exercise (Garcia-Ramos et al., 2018b). Garcia-Ramos et al. (2018b) also showed that mean velocity was more accurate for estimating 1RM bench press.

The method could be applied for a single exercise such as the bench press exercise. This would involve testing the mean velocity at 4–5 progressively increasing loads ranging from 40–80% 1RM. Jovanavic and Flanagan (2014) recommended using linear regression in a programme such as Microsoft Excel. This allows the practitioner to calculate the estimated 1RM by extrapolating the load–velocity regression line to the mean velocity threshold. The accuracy of the prediction will be increased if the minimal velocity threshold for the actual 1RM for that individual and exercise is known. Otherwise, an estimate of the value will need to be made using previously published data (e.g. Helms et al., 2017; Sanchez-Medina et al., 2010). It is also possible to extrapolate the load–velocity regression line to the intercept with 0 m/s (Jidovtseff et al., 2011).

An alternative approach can be to use fewer loads to estimate dynamic strength from velocity. Due to the time taken to measure multiple loads, the two-load or two-point method has been studied (Garcia-Ramos et al., 2018a; Jaric, 2016; Garcia-Ramos et al., 2018c). This method is simpler as it only requires two loads to be tested; for example, approximately 45% and 85% 1RM (Garcia-Ramos et al., 2018a). Therefore, the testing is less time intensive. The two-load method has been shown to be valid and reliable across a range of populations (Jaric, 2016; Garcia-Ramos and Jaric, 2019; Garcia-Ramos et al., 2018a). For example, Garcia-Ramos and colleagues (2018a) showed that the two-point method was highly reliable (CV < 5.1%) and valid for the bench press exercise. Rather than requiring testing across a range of loads or relying on a single external load, two loads allows enough points to compare between the different load–velocity capacities. The same method should be used consistently with retesting and avoid using direct and indirect assessments of 1RM interchangeably.

Different technologies have been used to estimate their validity and reliability for predicting 1RM (Bosquet et al., 2010; Balsalobre-Fernandez et al., 2018a; Perez-Castilla et al., 2019). For example, smartphone apps have been developed and researched for their potential to estimate 1RM (Balsalobre-Fernandez et al., 2018a). Other applications of velocity-based assessment and relevant technologies, as they relate to power, are discussed in more detail in Chapter 6.

Rating of Perceived Exertion

Methods based on the rating of perceived exertion (RPE) use subjective evaluation of exercises to estimate strength (Eston and Evans, 2009). Different RPE scales have been investigated with resistance training, including the Borg 6–20 scale (Borg, 1970), Borg category ratio 0–10 scale (Borg, 1982) and the OMNI RPE scale which uses visual representations to gauge exertion (Robertson et al., 2003). However, limited studies have investigated the effectiveness of using RPE to estimate 1RM (Naclerio and Larumbe-Zabala, 2017). Theoretically, due to the relationship between effort intensity and perception of effort, RPE could theoretically provide an indication of predicted strength (Cafarelli, 1982). Many studies have investigated the use of RPE as a method for assessing resistance training intensity without using it to estimate 1RM (Lagally et al., 2002; Day et al., 2004; Robertson et al., 2003). These studies have established a relationship between the intensity of resistance exercise and RPE. Eston and Evans (2009) showed that the Borg 6–20 RPE could accurately predict 1RM for the biceps curl and leg extension using loads in the 20–60% 1RM range.

The repetitions in reserve (RIR) rating of perceived exertion scale has been proposed as an effective method for estimating the intensity of a resistance training session (Helms et al., 2016). Measuring the number of repetitions that could potentially have been performed upon completion of the set provides an indicator of exertion. The RIR uses a 1–10 scale, with 10 indicating 1 RIR, 9 indicating 2 RIR and 0 indicating little to no effort (Zourdos et al., 2016b). However, this approach on its own is limited in terms of directly estimating 1RM and is more useful as a monitoring tool. A recent study explored the relationship between RIR and RPE as a method for estimating 1RM in powerlifters

(Balsalobre-Fernandez et al., 2018b). Incorporating RIR and RPE into the estimation equations appeared to increase the robustness of the load–velocity relationship for the back squat, bench press and hip thrust exercises. The RPE-based methods are an estimation, and as with other indirect methods, will contain some error. It is also important to take individual differences into account.

Attempts have also been made to develop ratings of perceived velocity (Bautista et al., 2014; Bautista et al., 2016). Bautista and colleagues (2016) validated the scale of perceived velocity in 11 young skiers performing the back squat. Velocity perception was highly accurate in this small sample, similar to a previous study performed with the bench press (Bautista et al., 2014). This method could be used to complement other prediction approaches and estimate dynamic strength, but requires further investigation.

Conclusion

The assessment of dynamic strength is a critical component of training programme design. Several methods are available that can directly or indirectly measure RM. The 1RM is considered the gold standard of assessment of maximal dynamic strength. However, other methods are available to researchers and practitioners that may allow for more efficient and ongoing assessment of dynamic strength. When using methods that predict the 1RM, researchers and practitioners need to be aware of the limitations, particularly when using it as the basis of programming.

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4

TESTING ISOMETRIC STRENGTH

Isometric Testing

Isometric testing is typically performed to determine the force–time characteristics of a body position performed by the individual. This type of testing has been used for strength assessment for many years. While dynamic strength assessment provides a good assessment of overall strength production, methods such as RM testing provide limited information on how force is produced. Conducting dynamic strength testing with large groups can also be time consuming. Isometric testing can provide overall force production capacity, but with the appropriate technology to measure time it can give the tester important insights with variables such as impulse (force × time) and RFD. It can also be performed more efficiently than RM testing as it removes the need for large numbers of warm-up sets before reaching the true maximum. Isometric testing is typically performed using a force plate, strain gauge or load cell technology. Isometric testing with the IMTP and isometric squat has shown to be highly correlated with 1RM strength across a range of exercises (Beckham et al., 2013; De Witt et al., 2018; Wang et al., 2016; McGuigan et al., 2010; McGuigan and Winchester, 2008; Bazyler et al., 2015). However, concerns have been raised by researchers regarding the specificity of isometric assessment and its relationship to dynamic performance (Wilson and Murphy, 1996; Murphy and Wilson, 1996).

Isometric testing also has potential to be useful for tracking rehabilitation due the ability to measure force without changing range of motion. Isometric assessment needs to be reliable and valid, so there is increasing interest in determining these aspects in different populations. Table 4.1 shows a summary of advantages and disadvantages of isometric testing.

TABLE 4.1 Advantages and disadvantages of isometric testing

Advantages	*Disadvantages*
Testing can be more efficient compared to dynamic testing	Lack of specificity to dynamic sports performance
Can be performed bilaterally or unilaterally	Requires specialised equipment such as force plates or strain gauges
Testing is highly reliable, particularly for peak force	
Easier to standardise the testing	
Less familiarisation required compared to other modes of strength testing	
Useful for rehabilitation monitoring	

Variables

Peak force is the most common variable measured via isometric testing. Peak force or the maximum force produced provides a measure of maximal strength. Force produced at specific time points is also commonly measured with isometric testing. Peak force is consistently shown to be highly reliable during isometric testing (Brady et al., 2018b; Bemben et al., 1992; Bishop et al., 2019). Strong relationships have also been shown between isometric peak force and performance in weightlifting (Haff et al., 2005), track cycling (Stone et al., 2004), throwing (Stone et al., 2003), golf swing head speed (Leary et al., 2012), sprinting (West et al., 2011; Wang et al., 2016), sprint acceleration (Brady et al., 2019), sprint kayak (Steeves et al., 2018) and jumping (Haff et al., 2005; Nuzzo et al., 2008).

RFD is another measure that can be assessed with isometric testing and provides an indication of the ability to produce force as quickly as possible. The rate at which force can be produced during a specific movement has been demonstrated to be related to range of abilities such as movement velocity, striking, strength and sprint performance (Maffiuletti et al., 2016; Khamoui et al., 2011; Leary et al., 2012; Wang et al., 2016). However, the reliability of these measures does not tend to be as high as with peak force (Brady et al., 2018a; Brady et al., 2018b; Comfort et al., 2015; Guppy et al., 2018). Due to the varying methods used by researchers, the relationships between RFD and dynamic performance have been inconsistent (Maffiuletti et al., 2016; Kawamori et al., 2006).

Different methods can be used to calculate RFD. Preset time windows can be used for determination of RFD and impulse such as 0–30, 0–50, 0–100, 0–150, 0–200 and 0–250 milliseconds (Haff et al., 2015). Other approaches have been to determine peak RFD over various time windows relative to onset of force (e.g. 100–200 msec; Penailillo et al., 2015). Another method has been to measure the average RFD over the entire slope of the force–time curve (Haff et al., 2015).

TABLE 4.2 Summary of variables assessed during isometric testing

Variable (Units)	*Definition*
Peak Force (N)	Measures the absolute (N), relative (N/kg) or allometrically scaled (N/kg$^{-\text{exp}}$) maximal force produced
Force (N)	Measures the absolute (N) or relative force (N/kg) produced at a specific time point (e.g. force at 100 msec)
Rate of force development (RFD) (N/s)	Measured in several ways from the relationship between force and time including overall, average, peak RFD and within specific time periods (e.g. 0–100 msec)
Impulse (N·s)	Integral of force–time
Starting strength (N)	Force at 50 msec
Index of explosiveness	The ability to produce force in the minimal amount of time
Reactivity coefficient	Ratio of the index of explosiveness to body mass
S-gradient	The RFD at the start of the movement (often calculated over the first half of the movement)
A-gradient	The RFD during the latter stage of the movement

Haff and colleagues (2015) demonstrated that using selected time bands for RFD was more reliable, whereas average RFD was shown to be less reliable. Peak RFD has also been measured as the maximal instantaneous slope of the force–time curve (Haff et al., 1997), but is less reliable than other RFD measures (Moir et al., 2019). The use of specific time bands provides more reliable measures of time specific variables during isometric testing (Guppy et al., 2018; Moir et al., 2019).

Impulse (integral of the force × time signal) can also be measured with isometric testing (Folland et al., 2014). Specific windows can also be analysed to allow insight into the time-sensitive aspects of force production. Impulse has been identified as an important aspect of performance and is receiving more attention in strength assessment (Chapter 6).

A range of different variables can be measured during isometric testing (Zatsiorsky and Kraemer, 2006). Table 4.2 shows a summary of measures that can be obtained. The evidence for the usefulness and relevance of all these measures has been mixed when applied to athlete populations (Harris et al., 2010).

Isometric Testing Guidelines

The reliability of isometric testing, particularly the RFD measures, can be improved with rigorous standardisation of the testing protocols (Comfort et al., 2019). For example, using wrist straps, tape and/or chalk can be useful for helping with grip during the IMTP. However, adhering to these protocols rigidly can be problematic when testing large groups of athletes, as it adds time to testing. Researchers and practitioners should record the conditions under which the testing was conducted, including body position and equipment setup (e.g. rack height for IMTP). Careful standardisation of the methods can improve validity and reliability of testing (Comfort et al., 2019).

A fundamental aspect of analysis of isometric characteristics is data acquisition and processing. Different guidelines are available that address these important areas (Comfort et al., 2019). Researchers and practitioners need to consider the initiation of the force production of the isometric action. This will be critical for the calculation of time-based variables such as RFD, which are typically measured within the first 250 msec of the action. Guidelines have been proposed for the starting point of the isometric action during the IMTP (Dos'Santos et al., 2017a). This can be defined as the point at which force production exceeds five standard deviations of the participant's body mass (Dos'Santos et al., 2017a). Research has suggested that using automated (algorithm-based) analysis results in higher reliability compared to manual methods of force onset detection for the IMTP (Carroll et al., 2019).

Consideration also needs to be given to sampling frequency and its impact on testing results (Dos'Santos et al., 2019). General recommendations are to sample at 1000 Hz when measuring time-dependent variables such as RFD and impulse (Maffiuletti et al., 2016; McMaster et al., 2014). However this may be unnecessary for calculating peak force which is more commonly measured by practitioners (Dos'Santos et al., 2019). A sampling rate of 500 Hz appears to be sufficient when measuring peak force and also force values at specific time points, such as 100, 150 and 200 msec (Dos'Santos et al., 2019). Following data collection, filtering and smoothing of the data also need to be considered. Based on current evidence, no clear consensus exists on the optimal methods that should be used (Comfort et al., 2019).

Isometric assessment can be used in conjunction with other strength and power assessments. For example, the DSD (sometimes referred to as the dynamic strength index, or DSI) has become a widely used assessment tool in strength and conditioning (Sheppard et al., 2011; Comfort et al., 2018a; Comfort et al., 2018b; Thomas et al., 2015a; Young et al., 2015). This measure combines the force produced during an isometric task and force production during a dynamic movement. By measuring the ratio between the peak force isometrically and dynamically (e.g. jumping or throwing) can provide insights into the training status of an athlete (Sheppard et al., 2011). Different approaches have been investigated for the DSD, including the lower body (Sheppard et al., 2011; Comfort et al., 2018a; Thomas et al., 2015a), upper body (Young et al., 2015; Young et al., 2014) and unilateral tasks (Bishop et al., 2018).

Isometric Mid-Thigh Pull

The IMTP has become arguably the most common isometric test used with athletes (Comfort et al., 2019). The test was first introduced by Haff and colleagues

(1997) in weightlifters utilising the clean pull performed isometrically at the second-pull weightlifting position. This was due to this position being where the highest forces and velocities are achieved in the clean and snatch in weightlifters (Garhammer, 1993). Since then it has been extensively studied and utilised by researchers and practitioners across a range of sports (Beckham et al., 2013; Brady et al., 2018b; De Witt et al., 2018; Kawamori et al., 2006; Moeskops et al., 2018; Suchomel et al., 2018). The IMTP peak force has consistently been shown to be highly reliable with ICCs ≥ 0.92 and CVs ≤ 5% (Haff et al., 2015; Thomas et al., 2015b). However, during the IMTP, RFD and other time-related variables are generally less reliable (Dos'Santos et al., 2019).

The effect of varying body position has been extensively studied with the IMTP (Beckham et al., 2018; Comfort et al., 2015; Dos'Santos et al., 2017c; Guppy et al., 2018; Guppy et al., 2019). Some confusion has existed with the terminology of "mid-thigh". Some researchers and practitioners have interpreted this a position at the mid-point of the thigh, rather than the higher second-pull position which was used in the original research (Haff et al., 1997). Most research has shown that differences are dependent on the body position adopted during the test (Beckham et al., 2018; Dos'Santos et al., 2017c; Guppy et al., 2018; Guppy et al., 2019) whereas one study has shown no difference (Comfort et al., 2015). For example, Guppy et al. (2018, 2019) tested 17 strength-power athletes across four different body positions in the IMTP, to assess between-session (Guppy et al., 2018) and within-session reliability (Guppy et al., 2019). Peak force measures varied across different positions. Reliable measures of peak force and time-specific force were found regardless of position. However, RFD measures were less reliable. In contrast, Comfort and colleagues (2015) showed no differences in peak force measures (or time-specific variables) across a range of different positions. Based on the current evidence it would seem pertinent to maintain a consistent position for retesting. As previously discussed, the second-pull weightlifting position with the trunk upright and slight knee bend appears to allow for the maximum force to be produced in the majority of individuals (Beckham et al., 2018; Guppy et al., 2019). Figure 2.2 shows the peak forces produced at different positions for a lifter.

Data processing is also an important consideration with isometric tests such as the IMTP (McMaster et al., 2014; Thompson, 2019). For example, one study investigated the effects of different sampling frequencies on IMTP kinetics (Dos'Santos et al., 2019). Sampling at different rates (500–2000 Hz) showed no significant differences in peak force, time-related force values (100, 150 and 200 msec) or RFD at specific time bands (0–100, 0–150 and 0–200 msec). Interestingly, the reliability of the measures was reasonably consistent. However peak force values were more reliable (ICC = 0.97, CV = 3.2%) compared to time-related force measures (ICC = 0.80–0.90, CV = 7.3–10.1%) and RFD measures (ICC = 0.81–0.93, CV = 14.2–24.1%). What appears to be most critical is to maintain the sampling frequency at the same level between testing sessions.

The effect of the type of instruction also needs careful consideration with the IMTP (Bemben et al., 1990; Halperin et al., 2016; Sahaly et al., 2001). The typical instruction that is given is to pull as hard and as fast as possible (Halperin et al., 2016). Brady and colleagues (2018b) also used the added instruction to push away from the ground and drive the feet into the ground and the bar from the floor. Strong verbal encouragement can positively influence the results (Belkhiria et al., 2018). As with all testing methods, the most critical factor is to apply the methods consistently between and within testing sessions to increase reliability and validity. Testers should also be mindful of an individual's preference, as some may not respond as positively to excessive verbal encouragement.

Researchers have utilised various setups for isometric testing and have developed portable systems which allow for cheaper alternatives to force plates (James et al., 2017; Till et al., 2018; Dobbin et al., 2018; Demura et al., 2010). These systems have utilised load cell, dynamometer and strain gauge technology. The reliability of some of these systems has been shown to be high with athlete populations (James et al., 2017), but the validity is more questionable (Till et al., 2018; Demura et al., 2010). Researchers and practitioners should determine the reliability and validity of these systems in their own settings with the populations they are working with.

Isometric testing can be conducted bilaterally or unilaterally. It has been more common to assess isometric strength bilaterally, but the increased availability and affordability of dual–force plate technology has led to the development of more effective unilateral testing (Bishop et al., 2018; Hart et al., 2012; Bishop et al., 2019). Peak and mean force have been shown to be reliable for both bilateral and unilateral isometric testing (Hart et al., 2012; Dos'Santos et al., 2017b). Bishop and colleagues (2019) showed that only peak force was reliable (CV < 5.7%) during unilateral isometric squat testing. Assessment of isometric strength has been used to assess imbalances (Kuki et al., 2019), both with bilateral (Bailey et al., 2015) and unilateral methods (Dos'Santos et al., 2017b; Bishop et al., 2019). A study by Kuki and colleagues (2019) compared unilateral and bilateral assessment of asymmetries during the IMTP. The results showed different degrees of asymmetries depending the testing mode, with larger asymmetries during bilateral versus unilateral testing. Therefore, researchers should specify the type of testing method that is being used to determine asymmetries. The practical applications of determining the asymmetries and the role for informing programming is discussed further in Chapter 10.

Isometric Mid-Thigh Pull Protocol

Pretesting practice sessions should be conducted to familiarise participants with the testing. If possible, provide at least one familiarisation session, particularly with individuals with little to no resistance training experience. The following steps can be followed when conducting the IMTP test:

- Perform a dynamic warm-up such as bodyweight squats or unweighted pulls (with broomstick). Practice trials at 50% and 75% of maximum effort can be performed.
- Ensure that the correct body position is maintained throughout the test with standardised grip and feet width. The typical setup for the IMTP is outlined in Table 4.3.
- Straps, tape or chalk can be used for the IMTP to limit the impact of inadequate grip strength.
- A certain degree of pretension can be produced prior to the initiation of the test (typically less than 50 N) to ensure a strong position at the start of the test. A cue such as "apply steady tension on the bar" can be used (Travis et al., 2018).
- No countermovement is allowed prior to the initiation of the isometric action (based on visual inspection) (Maffiuletti et al., 2016).
- Countdown to the performance of the test with "3, 2, 1, Go!"
- The instruction to "pull as hard and fast as possible, while pushing into the ground" should be used.
- Allow the subject to perform 2–3 maximal trials. Due to the high within-session reliability of isometric tests, there is no need to perform excessive trials.
- A rest period of approximately 1 minute can be allowed between trials.
- As a rough guide, two trials that are within 250 N of each other can be used as a criteria to terminate the testing (Kraska et al., 2009). If the participant continues to improve, then testing can continue.

TABLE 4.3 Setup for isometric mid-thigh pull (IMTP) and isometric squat tests

	Isometric Mid-Thigh Pull (IMTP)	*Isometric Squat*
Trunk	Upright	Upright
Hip	140–150°	120–150°
Knee	120–145°	90–120°
Grip	Overhand (straps or tape optional)	Overhand
Instruction	Pull as hard and fast as possible, while driving feet into the ground	Push as hard and fast as possible, while driving feet into the ground
Tension	Apply steady tension to the bar prior to initiation of test	Apply steady tension to the bar prior to initiation of test

- Strong verbal encouragement can be used throughout the test (Belkhiria et al., 2018).
- Isometric position should be held for 3–5 seconds.

For the processing of the testing date, the following general recommendations are made:

- For time-specific values, an offset threshold of five times the body mass standard deviation should be used to determine the start of the isometric action (Dos'Santos et al., 2017a).
- A sampling rate of 500 Hz is sufficient for peak force measurement (and most time-related variables).
- Results can be reported as an average of trials or best performance. While the research is not consistent on this issue, it does not appear to matter which method is used if it is used consistently.
- Peak force can be reported as absolute force, relative to body mass and allometrically scaled ($N/kg^{-0.67}$). No consensus currently exists on which approach to use when presenting the results (Jaric, 2002; Suchomel et al., 2018).

Isometric Squat

The isometric squat is also commonly used to assess isometric strength in a range of populations (Brady et al., 2018b; Bazyler et al., 2015; Drake et al., 2018). Isometric squat peak force has consistently been shown to be reliable across a range of positions (Bazyler et al., 2015; Blazevich et al., 2002; Drake et al., 2018; Rahmani et al., 2001). Isometric squat peak force is also highly correlated with 1RM back squat performance (Blazevich et al., 2002; Drake et al., 2018; Nuzzo et al., 2008). Variables measured during the isometric squat have also been shown to be related to athlete performance (Tillin et al., 2013).

Researchers have compared the isometric squat and IMTP performed at the same knee and hip angles (Brady et al., 2018b; Nuzzo et al., 2008). Participants produced greater peak force and impulse (0–300 msec) in the isometric squat compared to the IMTP. Peak force measures were highly reliable for both the isometric squat and IMTP. Both tests were demonstrated to be useful for detecting meaningful changes in force capacity of participants. The authors suggested that if researchers and practitioners are interested in determining the true maximum lower body force capacity of athletes then the isometric squat should be preferred (Brady et al., 2018b).

Body position has also been studied in the isometric squat (Palmer et al., 2018; Marcora and Miller, 2000; Paulus et al., 2008). One study demonstrated that higher peak force values were achieved in the quarter-squat position compared to full- and half-squat positions (Palmer et al., 2018). The peak force measures were also more reliable than RFD measures used in the study (Palmer et al., 2018). Another study found differences in maximum isometric force (normalised for bodyweight) between five different knee angles (90–170°) in 24 resistance-trained participants (Paulus et al., 2008).

The isometric squat may require more familiarisation compared to the IMTP (Drake et al., 2018). Drake and colleagues (2018) showed that even with well-trained participants three familiarisation sessions were required before stabilisation of peak and relative peak force occurred in the isometric squat. As with the IMTP, constant tension should be applied to the bar prior to the initiation of the test (Bazyler et al., 2015). Excessive force production prior to the start of the test should be avoided, with greater than 50 N a general guideline. In general, greater peak force values have been found with the isometric squat compared to the IMTP (Brady et al., 2018b). Therefore, it is important that researchers and practitioners not use these tests interchangeably. Table 4.3 outlines a potential setup for the isometric squat. The same general guidelines for conducting and analysing the IMTP test can be followed.

Isometric Leg Press

Instrumented leg presses have also been used for assessment of isometric force capabilities (Zaras et al., 2016; Bogdanis et al., 2019; Baur et al., 2016; Harden et al., 2018b; Spiering et al., 2011; Harden et al., 2018a). Isometric assessment using leg press has been shown to be reliable across a range of positions (ICC 0.90–0.95) (Bogdanis et al., 2019). The researchers in one study (Bogdanis et al., 2019) used Kinovea video analysis software to measure the knee angle during the isometric testing. Another study measured the reliability and sensitivity of an instrumented leg press at two angles (90° and 120°) in 35 strength-trained men (Harden et al., 2018a). The reliability of force output was high with ICC = 0.96 and CV < 5%. Force production was higher in the 120° position, again highlighting the importance of position when using isometric assessments. Compared to other movements, the isometric leg press has not been studied as extensively, so more work is required to determine the reliability of the test across a range of populations.

Other Lower Body Tests

A variety of other tests have also been investigated to assess lower body position–specific isometric strength (McCall et al., 2015; Ryan et al., 2019; Light and Thorborg, 2016; Hickey et al., 2018; O'Brien et al., 2019; Matinlauri et al., 2019). For example, McCall and colleagues (2015) measured the isometric force of the posterior upper legs while in a supine position at two different knee angles (30° and 90°) using a force plate in professional soccer players. The testing was shown to be reliable and sensitive to changes in force reduction following a competitive soccer match. Matinlauri et al. (2019) evaluated the reliability of a similar test but in a standing position with different knee angles compared to the McCall et al. (2015) study. Isometric strength testing has also been investigated as a method for tracking abduction and adduction strength in Australian rules football players (Ryan et al., 2019; O'Brien et al., 2019) and soccer players (O'Brien et al., 2019). Using load cell technology, isometric force can be measured in different hip positions. For example, the reliability of this approach was acceptable when used with elite Australian rules football players (CV = 6.3%) (Ryan et al., 2019).

Upper Body Isometric Testing

Isometric Bench

While a great deal of the literature has focused on lower body tasks, upper body isometric assessments have also been investigated (Young et al., 2015;Young et al., 2014; Murphy et al., 1995; Steeves et al., 2018). To assess isometric characteristics in the bench press requires a setup that allows force to be measured with equipment such as a force plate (Young et al., 2014). Load cells can also be used for these types of assessments.

The reliability of bench press isometric strength characteristics has been investigated in athlete populations (Young et al., 2014; Murphy et al., 1995). As with other isometric tests, peak force measures are highly reliable (CV < 4%) (Pritchard et al., 2019;Young et al., 2014). Time-related characteristics tend to be less reliable with CV's > 6% (Young et al., 2014).

Body position has been investigated in the isometric bench press (Murphy et al., 1995;Young et al., 2014). The findings of one study showed that the peak force and RFD varied significantly using different body positions (90° degrees vs 120°) (Murphy et al., 1995). Another study found significant differences in peak force between different elbow positions (60°, 90°, 120° and 150°) (Young et al., 2014). The highest peak force values were produced at 120° and 150°. This supports using a consistent body position for isometric testing and not using positions interchangeably. The DSD has also been investigated for the bench press and was shown to be highly reliable (CV = 3.5%, ICC = 0.93) (Parsonage et al., 2018; Young et al., 2015;Young et al., 2014).

Isometric Upper Body Tasks

In addition to bench press, other upper body isometric tasks have been studied (Ashworth and Cohen, 2019;Ashworth et al., 2018; Steeves et al., 2018). Ashworth and colleagues (2018) investigated reliability of a novel shoulder isometric test using force plates in rugby union athletes (ICC = 0.94–0.98), CV = 5.5–11.3%). Steeves et al. (2018) determined the reliability and validity of an isometric trunk assessment utilizing several different positions in elite sprint kayakers. The CVs for the peak force on these tests ranged from 2.4–7.7%. Importantly, there were large correlations with on-water performance with several of the tests (Steeves et al., 2018). As with all tests, researchers and practitioners should look to determine the reliability of these tests in their own populations.

An additional advantage of isometric tests is that they can isolate specific muscles and joint angles. Isometric tests have been developed for both upper and lower body that can assist with classification of Paralympic athletes (Beckman et al., 2014; Beckman et al., 2017; Connick et al., 2018). Importantly, in addition to assisting with classification of athletes, several of these isometric tests have been shown to be highly related to performance (Connick et al., 2018).

Isometric Grip Strength

Grip strength testing has been a staple of fitness testing batteries for many years (Cronin et al., 2017; Burke et al., 1953). The test is particularly popular with clinical populations due to its ease of use and high reliability (Garcia-Hermoso et al., 2018; Roberts et al., 2011). Grip strength has been reported to be a good predictor of physical performance in older adults (Stevens et al., 2012). However, other research has indicated its limitations as a measure for tracking strength performance in older adults (Tieland et al., 2015).

Grip strength has been shown to be important in athlete populations and has been studied extensively in a range of sports (Cronin et al., 2017). A variety of dynamometers are available for testing grip strength. A key recommendation is to use the same dynamometer consistently (Cronin et al., 2017). As with other forms of isometric testing, consideration needs to be given to aspects such as familiarisation, body position (e.g. seated versus standing), hand dominance and testing protocol. The relationship between grip strength and dynamic measures of strength tends to be quite poor across a range of populations (Rogers et al., 2017; Milliken et al., 2008).

Researchers have examined the relationship between hand grip dynamometry and isokinetic testing (Whiteley et al., 2012; Martin et al., 2006; Stark et al., 2011; Mentiplay et al., 2015). Using a hand grip dynamometer, it is possible to test other movements, such as knee flexion and extension. Interrater reliability was shown to be high using the dynamometer, along with moderate to high relationships to isokinetic measures in 216 professional soccer players (Whiteley et al., 2012). High reliability reported for hip and knee isometric strength in older adults measured using handheld dynamometry (Arnold et al., 2010). In general, this approach appears to be reliable and valid across different joint actions in clinical populations (Stark et al., 2011). However, using handheld dynamometry has been shown to underestimate isometric quadriceps strength in stronger older adults (Martin et al., 2006).

The general guidelines that have been outlined for IMTP and isometric squat testing can be applied to increase reliability (Table 4.4).

TABLE 4.4 Guidelines for increasing reliability of isometric testing

Allow for adequate familiarisation with the isometric task (at least one session if possible).
Consistent posture (standing or seated) and wrist, elbow and shoulder position maintained.
Perform a minimum of three trials with 1 minute rest between efforts.
Tension throughout the test is maintained for 2–5 seconds.
Peak or average of trials can be used for analysis.
Standardise all testing conditions between trials and testing sessions.

Isometric Dynamometry

Traditionally, isometric force–time characteristics have been assessed in exercise science via dynamometry (Tillin et al., 2018). Different isokinetic dynamometers are available, such as Humac Norm, Biodex and Cybex. The advantage of these methods is it allows the testing to be performed under controlled conditions. The most common test is the leg extension test performed at a variety of different knee angles (Whiteley et al., 2012; Verdijk et al., 2009). Other common body positions such as plantar flexion have been studied (Webber and Porter, 2010).

With isometric testing it is possible to measure across a range of angles and body positions. Researchers and practitioners need to determine which body positions provide useful information for the population they are working with. A general recommendation is to use the body position and joint angles that allows peak force to be developed. Adequate familiarisation needs to be provided but is typically less than is needed for dynamic testing. One of the disadvantages with using isokinetic dynamometry is that it requires specialised and expensive equipment.

Peak torque or maximum voluntary contraction is commonly measured via dynamometry to assess isometric strength (McKendry et al., 2019; Thompson, 2019; Francis et al., 2017; Kordi et al., 2017; McKinlay et al., 2017; Sugiura et al., 2016; Thompson et al., 2013; Webber and Porter, 2010; Verdijk et al., 2009). In general, similar testing guidelines can be applied as with other isometric protocols. Three trials with a rest period of 1 minute between trials is generally recommended. Standardised, consistent verbal encouragement should be used as variation in verbal instructions results in differences in peak force and RFD.

Low-cost dynamometers have been investigated as alternatives to these more expensive methods (Romero-Franco et al., 2019; Romero-Franco et al., 2017). In general, low-cost dynamometers have demonstrated acceptable reliability and validity across a range of joint actions (Romero-Franco et al., 2019; Romero-Franco et al., 2017).

Conclusion

Isometric assessment can provide researchers and practitioners with reliable and valid measures of maximal force production. Peak force is the most reliable measure obtained during isometric assessment. Time-related measures such as RFD tend to be less reliable. Different tests are available for isometric assessment, including the IMTP, isometric squat, isometric bench press and range-of-position lower and upper body tests. Researchers and practitioners should use consistent testing protocols between sessions to ensure maximum reliability.

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5

TESTING ECCENTRIC STRENGTH

Eccentric Testing

Eccentric (lengthening) contractions produce greater levels of force compared to concentric (shortening) contractions (Franchi et al., 2017; Komi, 1973). Eccentric strength is an important component of athlete performance (Douglas et al., 2017b). For example, eccentric strength has been shown to be a critical aspect of change of direction performance and ability to decelerate (Spiteri et al., 2014; Jones et al., 2017). Eccentric strength is also critical for performing rapid stretch shortening cycle activities such as jumping (Bridgeman et al., 2018). Therefore, training methods to improve eccentric strength are used in athlete programmes (Suchomel et al., 2019b; Cowell et al., 2012; Suchomel et al., 2019a). It may also play a role in injury prevention, with eccentric strength being shown to be important for helping to decelerate at the end range of motion (Spiteri et al., 2014). Researchers have shown that deficits in eccentric strength remain following rehabilitation (Bourne et al., 2019). In elite female Australian rules football players, these deficits in knee flexor eccentric strength can remain up to 10 years following ACL reconstruction (Bourne et al., 2019). Eccentric strength has also been demonstrated to be vital for populations such as older adults (Gluchowski et al., 2015; Roig et al., 2010; Hortobagyi et al., 2001). Due to its importance with deceleration and change of direction ability, increasing eccentric force capability may also contribute to decreased risk of falls and improved balance (Gluchowski et al., 2017).

Many sports require the ability to tolerate large eccentric forces (Franchi et al., 2019). Therefore, being able to assess high-load eccentric strength can provide useful insights into athlete performance. For example, a sport such as alpine skiing involves high impact levels (Berg et al., 1995), with eccentric strength shown to be important in these types of sports (Franchi et al., 2019). Measuring eccentric strength can provide information about the responses to a training programme (Douglas et al., 2017a). However, eccentric-only testing has not been studied as extensively as other modes of testing (Harden et al., 2019). This is no doubt due to the increased difficulties associated with eccentric testing. Due to participants being stronger during the eccentric phase, relatively heavier loads are required for testing. Therefore, this mode of testing presents challenges to provide large eccentric loads safely for testing, particularly for stronger athletes. Eccentric contractions can also result in greater amounts of delayed onset muscle soreness (DOMS) which needs to be accounted for when testing clinical populations (Nosaka and Newton, 2002). Decrements in force output can remain for several days following unaccustomed eccentric exercise (Sayers and Clarkson, 2001; Mackey et al., 2004). Another aspect that presents difficulties with eccentric testing is the ability to control velocity during the movement. Most of the research has been conducted using isokinetic testing which may have limited application to practical settings. Therefore, researchers and practitioners have become more interested in isoinertial testing options for assessment of eccentric strength.

Eccentric devices have been developed for training eccentric strength qualities but are less suited for assessment purposes (Tinwala et al., 2017). While most of these devices are used for vertical eccentric-based movements, horizontal devices have also been developed for training of athletes (Tinwala et al., 2017). Developing systems that could also be used for accurately testing these eccentric qualities would be useful for researchers and practitioners.

Eccentric Variables

Measurement of eccentric strength has been shown to be highly reliable (Frohm et al., 2005; Bridgeman et al., 2016; Hollander et al., 2007; Opar et al., 2013; Harden et al., 2019). As with other testing modes, peak force measures are reliable (Harden et al., 2018), although in some studies this is less than what has been reported for concentric strength (Stock and Luera, 2014). Time-dependent variables such as RFD can also be measured during eccentric testing but have lower reliability (Pryor et al., 1994; Murphy et al., 1994; Nibali et al., 2015).

Systems have been developed that can measure eccentric strength unilaterally and subsequently have the potential to investigate asymmetries (Opar et al., 2013). However, bilateral assessment of eccentric strength is more reliable than unilateral assessment (Opar et al., 2013). Eccentric velocity has been shown to be useful for maximising adaptations to eccentric training (Bogdanis et al., 2018; Paddon-Jones et al., 2001; Mike et al., 2017; Stasinaki et al., 2019). Therefore, it is important to be able to measure eccentric velocity accurately and reliably. This remains a challenge, particularly in practical settings.

Due to the challenges of measuring eccentric only strength, it can be insightful to investigate eccentric characteristics during vertical jumping (Nibali et al., 2015;

Cormie et al., 2010; Jordan et al., 2018; Moir et al., 2018). For example, Jordan and colleagues (2018) measured eccentric impulse characteristics during CMJ and static jumps (SJ) in alpine ski athletes and ski cross athletes. Adolescent ski race athletes showed different eccentric characteristics (lower deceleration impulse) compared to elite athletes. Testing was conducted using a dual-force plate system which allowed for analysis of asymmetries. Ratios have also been examined with other eccentric testing mode such as isokinetics (Impellizzeri et al., 2008). The reliability of some of these ratios has been questionable, and researchers and practitioners should consider these within their own populations being tested (Impellizzeri et al., 2008).

Researchers have also investigated the eccentric characteristics during landing tasks such as drop jumps (Moir et al., 2018). Moir and colleagues (2018) compared eccentric and concentric force–velocity characteristics across a range of loads in jump squats and drop jumps. Use of CMJ and drop jumps, along with unloaded and loaded SJ, was able to characterise eccentric force–velocity characteristics in resistance-training men. Testing force–velocity characteristics in jumping is discussed in more detail in Chapter 7.

Strength can vary depending on the mode of testing. Just because an individual is strong isometrically does not mean they are as strong eccentrically (Harden et al., 2019). For example, strength testing can be used to assess distinct force-production qualities. Harden and colleagues (2019) showed that participants had different strength capacities depending on the mode of testing that was used (dynamic, eccentric or isometric). Therefore, practitioners should avoid using strength results collected from other modes of testing, such as isometric or dynamic testing, to prescribe training loads for eccentric training. It is vital to not rely on a single measure of strength. Individual differences have also been shown to exist in the ratio of concentric to eccentric strength (Bridgeman et al., 2018). This provides further support to the notion that different strength qualities need to be considered when prescribing training and not be used interchangeably. Figure 5.1 shows the eccentric and concentric testing results for several athletes.

Researchers have attempted to estimate eccentric isokinetic strength from other testing variables (Kellis et al., 2000). These approaches are problematic due the large variation that can occur between eccentric and concentric torque values, with 20–100% greater eccentric to concentric values being reported (Kelly et al., 2015; Enoka, 1996). Differences will occur depending on the mode of testing and joint(s) being tested.

Eccentric Testing Methods

Different exercise modes have been used to assess eccentric strength qualities (Murphy and Wilson, 1997; Harden et al., 2018; Opar et al., 2013; Ferley and Vukovich, 2019; Stock and Luera, 2014; Harden et al., 2019). Isokinetic devices have been used extensively to assess eccentric strength qualities (Bridgeman et al.,

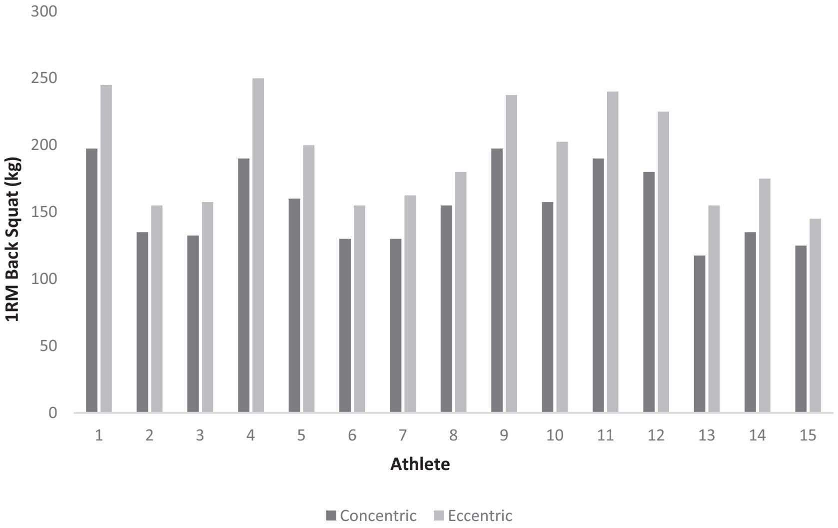

FIGURE 5.1 Individual differences in eccentric and concentric strength

2016; Walker et al., 2016; Farthing and Chilibeck, 2003; Aagaard et al., 1998; Wilson et al., 1997; Hortobagyi et al., 2001; Impellizzeri et al., 2008; Ardern et al., 2015). As discussed previously, eccentric strength qualities are specific to the testing mode. Therefore, it is critical to be aware of the mode of testing being used when analysing the results and comparing to previously published findings. The results obtained from different modes of eccentric assessment will not necessarily be comparable. Dynamic constant external resistance is another common method used to assess eccentric strength (Sabido et al., 2017; Hollander et al., 2007; Bogdanis et al., 2018; Kelly et al., 2015). As with isometric testing, load cells and strain gauges have been used for the assessment of eccentric strength (Opar et al., 2013; Chalker et al., 2018; Chalker et al., 2016; Doss and Karpovich, 1965).

Investigations have assessed eccentric strength with handheld dynamometers (Cools et al., 2016; Johansson et al., 2015). Rotator cuff strength was assessed using isokinetic dynamometry and handheld dynamometry with strong correlations shown between the two modes ($r = 0.70–0.78$) (Cools et al., 2016). This type of testing has also been investigated in overhead athletes from sports such as volleyball, handball and tennis (Cools et al., 2016). High reliability was reported with the eccentric testing via handheld dynamometry (ICC = 0.86–0.89).

Harden and colleagues (2018) investigated an eccentric testing method that could be implemented in an applied setting. The study used a pneumatic leg press instrumented with force plates that could measure eccentric strength loaded supramaximally (Harden et al., 2018). However, this method still requires specialised equipment that would not be readily available in all practical settings.

TABLE 5.1 Advantages and disadvantages of different eccentric testing methods

	Advantages	*Disadvantages*
Dynamic constant external resistance	Easier to implement into a testing programme Lower cost compared to commercial systems	Difficult to control velocity of the movement eccentrically Only provides a limited amount of information on eccentric characteristics Requires spotters and additional assistance for eccentric loads
Isokinetic assessment	Provide a range of different variables for analysis Perform the testing under more controlled conditions Perform single-joint assessments	Expensive equipment required Easier to measure and control the velocity of the eccentric phase Concerns over validity of isokinetics and lack of specificity to sports performance

Spotters and close supervision are required for any eccentric testing. As the individual will be stronger on the eccentric phase of the lift (by approximately 20–30%), safety is paramount when performing this type of testing. Specialised systems have been developed which assist with the concentric phase of the movement (Stasinaki et al., 2019; Douglas et al., 2018). Smith machines are well suited to this with motor-assisted devices used to lift the barbell to the starting position for testing or training (Stasinaki et al., 2019). If these types of setups are not available, several spotters would be needed to complete the testing safely. Any testing protocol will need to be effective and able to measure eccentric strength accurately. Different aspects of the testing need to be controlled as much as possible and kept consistent between trials and sessions to increase reliability. The advantages and disadvantages of dynamic constant external resistance and isokinetic systems are shown in Table 5.1.

While there is little published research on dynamic constant resistance eccentric tests, some guidelines are available (Refsnes, 1999; Popper, 2001). Maximal eccentric strength testing as proposed by Refsnes (1999) can be performed with the back squat. To measure force, the test should be performed on a force plate. Alternatively, a linear position transducer (or device for measuring velocity) could be used as an alternative. The full range of motion is used to the bottom position of the squat (i.e. full depth). One criterion is that the velocity and force are constant throughout the range of motion and the lift lasts greater than 3.5 seconds. Using a metronome or some other timing device can help control the descent of the eccentric phase. Setting criteria for the force decline (e.g. greater than 5%) is one approach that has been used to define a stable eccentric force throughout the range of motion (Harden et al., 2018). Another recommended criteria is to maintain the force level above 97% of the average force before the end of the lift (Refsnes, 1999). While these types of tests have been used in practice, particularly with elite athletes, limited published research has looked at the reliability and efficacy of such tests (Horn et al., 2002; Kelly et al., 2015; Popper, 2001). Horn et al. (2002) investigated the reliability of a back squat eccentric test in eighteen strength trained men with at least 1 year of resistance-training experience. The reliability of the test was high (ICC = 0.99) and was highly correlated to the isometric squat test ($r = 0.76$) (Horn et al., 2002).

Kelly and colleagues (2015) used a mechanical hoist system to return the weight to the start following an eccentric bench press test. The same could be achieved using spotters to lift the weight to the start position, which is what happens following a failed attempt with the squat and bench press exercises during a powerlifting competition. In the study by Kelly et al. (2015) a missed attempt was defined as a lift where the participant was unable to maintain the velocity for at least 3 seconds using a metronome. Hollander and colleagues (2007) tested 1RM eccentric strength in different exercises using a similar protocol. In another interesting aspect to the Kelly et al. (2015) study, they compared the number of repetitions that could be performed at different percentages of maximum for both eccentric and concentric 1RM. Significant differences were observed at the 90% 1RM test. This has significant implications for practitioners prescribing training loads off maximal testing data.

As with other modes of strength testing, different factors can have an impact of the testing results. For example, during eccentric isokinetic testing, visual feedback has been shown to improve peak eccentric moments (Kellis and Baltzopoulos, 1996). Chalker and colleagues (2018) showed increased peak eccentric force using real time visual feedback in cricket players. Therefore, these factors should be controlled as much as possible during testing sessions.

Maximal Eccentric Testing Protocol

- At least one, if not more, familiarisation sessions with the test should be conducted (Hahn, 2018). This is particularly vital if the participant has not performed eccentric training or testing before.
- Excessive DOMS can be reduced by taking advantage of the repeated bout effect (Nosaka et al., 2001). Significant protection from DOMS can be afforded from just 1–2 sessions of lower-intensity eccentric exercise (Nosaka et al., 2001).
- Ensure the participant is thoroughly warmed up with several repetitions performed with the exercise eccentrically.
- One of the requirements of a valid eccentric strength test is the capacity to control the velocity. For example, during the eccentric phase of a bench press or squat the descent velocity needs to be controlled and measured. A metronome can be used to help maintain a constant velocity.
- Range of motion for the end of the test needs to be defined clearly (e.g. bench press touching the test, back squat to correct depth).

- Duration of the eccentric test should be at least 3–3.5 seconds (Kelly et al., 2015).
- Velocity and force of the lift is maintained within 3% of the average overall levels.
- An adequate rest period of 3–5 minutes should be allowed between attempts.
- Avoid having more than 2–3 maximal attempts.
- Safety of the lifter and spotters is paramount. Ensure that adequate supervision is available, and spotters and testers are well versed in the testing protocols.

Conclusion

Characteristics of eccentric strength are important for performance and health. However, testing methods and equipment for eccentric strength are less readily available compared to other methods. While eccentric testing is not as commonly used in research and practice, it provides useful information for practitioners. Different modes of eccentric testing can be used but should not be used interchangeably. Several variables can be measured with eccentric strength assessment with peak force the most reliable. Eccentric testing needs to be performed under controlled conditions with attention paid to lifter safety and velocity of the eccentric phase.

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6

POWER

Importance of Power

Power is a key aspect of athletic performance (Garhammer, 1993; Cormie et al., 2011a; Haugen et al., 2018). The ability to perform fundamental movements such as jumping, throwing and sprinting are underpinned by power. Team sports, martial arts, gymnastics, swimming and diving, along with racquet sports, will require well-developed levels of power. Therefore, it is an integral component of athlete training programmes (Cormie et al., 2011b). Profiling of power characteristics is commonly used to evaluate athletes and their responses to training programmes (McMaster et al., 2016; McMaster et al., 2014). However, power is not only critical for athletes. Power has also been shown to be important for other populations such as tactical athletes (police, military, firefighters) (Barringer et al., 2019) and has implications for overall health. Evidence suggests that power is even more vital than other capacities such as strength and endurance for older populations (Byrne et al., 2016). For example, studies have shown that power declines at a faster rate than strength in older adults (Byrne et al., 2016; McKinnon et al., 2017; Skelton et al., 1994; Izquierdo et al., 1999a). In particular, the velocity component of power appears to be crucial for performing activities of daily living in older adults (Pojednic et al., 2012; Reid and Fielding, 2012; Bassey et al., 1992). The ability to produce velocity is negatively impacted by aging when compared to neuromuscular characteristics of younger populations (Toji and Kaneko, 2007). Given the importance of these characteristics for clinical populations, power-based resistance training has been recommended for improving functional status (Byrne et al., 2016; Evans, 2000). Therefore, accurate measurement of power qualities is critical for all populations.

Measurement of Power

Accurate measurement of power starts with clearly defining the concept of power. Power refers to the rate at which work is performed and can be considered as force times velocity. Research has shown that power can be improved by either increasing the force component (strength) or velocity component (displacement over time) (Suchomel et al., 2016). It has been previously established that strength (force) is an integral component of power and that these two aspects are closely related (Suchomel et al., 2016; Cormie et al., 2010b). Load–velocity profiling has been studied extensively in many different populations and contexts and can provide critical information about an individual's response to load (Rahmani et al., 2001; McMaster et al., 2014).

Calculation of power, terminology and its importance has received much attention from researchers (Cormie et al., 2007a; Cormie et al., 2007b; Winter et al., 2016; Li et al., 2008; Dugan et al., 2004; Knudson, 2009). As with any other physical capacity, the assessment method used will be critical. Several researchers have expressed concern over incorrect usage of power terminology and how it is applied in exercise science (Knudson, 2009; Winter et al., 2016). Therefore, using consistent and accurate terminology when discussing power is needed.

As power consists of force, time and displacement, it is these aspects which are the focus of measurement. Different technologies can be used to measure power including force plates, linear position transducers, accelerometers, videography, contact mats and various timing devices. Methods can be used to estimate muscular power based on measures of displacement and velocity. Several different approaches have been used in the literature which can make comparison between studies difficult. With regards to resistance training, differences in exercises tested can also make comparing studies problematic. Ultimately, the method used will be determined by budget and technology available. As with other testing qualities, researchers and practitioners should appreciate the reliability and validity of the methods being used.

Along with the different technologies available, a plethora of tests are available for power assessment (McGuigan et al., 2013; McMaster et al., 2014). It is important to be aware of the different tests, variables measured and how these are calculated when making comparisons between studies (Hori et al., 2006; McMaster et al., 2014). Assumptions and limitations of the methods also need to be considered to allow the researcher and practitioner to make informed decisions about their use. The different tests that can be used for power assessment are presented in Chapter 7.

Jump height is often used as a surrogate for muscular power, with vertical jump testing one of the most common assessments used by strength and conditioning practitioners (Jones et al., 2016). Various equations have been developed to estimate power from jump height (Canavan and Vescovi, 2004; Sayers et al., 1999; Lara-Sanchez et al., 2011; Duncan et al., 2008; Quagliarella et al., 2011). However, the equations have limitations due to the number of assumptions that are made (Morin et al., 2019). While measurement of jump height is a useful performance measure, its ability to estimate power is more questionable.

Several different variables can be measured within the context of power (Table 6.1). For example, there is debate on the utility of peak power (highest peak instantaneous power), with some researchers suggesting that mean power (average power over the entire movement) is a more useful measure (Loturco et al., 2017). Impulse has also been suggested as a more important variable, particularly for jumping tasks (Kirby et al., 2011; Lake et al., 2018b; McBride et al., 2010). Impulse has been studied during loaded and unloaded jumping (Kirby et al., 2011; Mundy et al., 2017). Rather than continuing to focus solely on outputs such as peak power, how force is produced within the context of time and displacement should also be considered (see Chapter 9).

The question of optimal loading for power has been addressed in many studies (Bevan et al., 2010; Cormie et al., 2007e; Dugan et al., 2004; Kilduff et al., 2007; Lawson et al., 2019; Baker et al., 2001b; Baker et al., 2001a; Rahmani et al., 2001). For some time, researchers have attempted to identify the load at which peak power output occurs in a range of different exercises (Cormie et al., 2007c; Dugan et al., 2004; Hori et al., 2007; McBride et al., 1999; McBride et al., 2011; Soriano et al., 2015; Soriano et al., 2017; Argus et al., 2014; Argus et al., 2011; Harris et al., 2007; Kawamori et al., 2005; Alcaraz et al., 2011). Generally, the load is based on a percentage of 1RM (see Chapter 3). What is clear from this body of work is that no single "optimal" load exists and that load varies depending upon factors such as the exercise (Fernandes et al., 2018b; Orange et al., 2018a), training level (Soriano et al., 2017; Soriano et al., 2015; Loturco et al., 2018b; McBride et al., 2011; Miller et al., 2019; Baker, 2001), age (Fernandes et al., 2018b; Izquierdo et al., 1999b, 1999a; Candow and Chilibeck, 2005; Petrella et al., 2005; Miller et al., 2019) and equipment used (Hori et al., 2007; Garcia-Ramos et al., 2016). All these factors make comparison between studies difficult and limit firm conclusions about what constitutes "optimal" load for training. Some evidence suggests that training at these optimal loads maximises the responses to training (Loturco et al., 2018a). However, the majority of research shows that training at a range of loads is an

TABLE 6.1 Variables related to power

Variable	*Measure*	*Units*
Jump/push height	Displacement	Metres (m)
Peak/mean power	Force × velocity	Watts (W)
Peak/mean velocity	Displacement/time	Metres per second (m/s)
Flight time	Time off the ground	Time (s)
Impulse	Force × time	Newton seconds (N·s)
Contact time	Ground contact time	Time (s)

effective method for improving power (Toji and Kaneko, 2004; Cormie et al., 2007d; de Vos et al., 2005).

Research and practice have often focused on power variables and absolute measures. However there is increasing interest in the value of time-series aspects of these metrics and analysis of curves to investigate movement characteristics (Parker and Lundgren, 2018; McMahon et al., 2017a; McMahon et al., 2017b; Suchomel and Sole, 2017; Cormie et al., 2009; Perez-Castilla et al., 2018; Eagles et al., 2017). These approaches can be informative for providing insight on how movement is produced during dynamic tasks such as jumping. For example, Parker and Lundgren (2018) used principal component analysis to analyse the force–time curves during CMJs performed by surfers and golfers, with different waveform characteristics being exhibited depending on the sporting background of the athletes. These concepts are discussed further in Chapter 9.

Eccentric characteristics of power have also been investigated (Cormie et al., 2010a). As discussed in Chapter 5, eccentric force is a critical component of performance. Eccentric power should a different pattern compared to concentric power and has the potential to provide unique insights into performance (Cormie et al., 2010a).

Force Plates

Force plates have been used to measure power during movements such as vertical jumping by biomechanists for many years (Cavagna, 1975; Komi and Bosco, 1978; Major et al., 1998; Ramey, 1975; Payne et al., 1968). Force plates are considered the gold standard for the measurement of power, particularly for jumping tasks (Owen et al., 2014).

Methodological considerations need to be taken into account when using force plates for testing power (Owen et al., 2014). Factors to consider include triaxial versus uniaxial force plates, sampling frequency and criteria for the start of the movement (McMaster et al., 2014). The recommended sampling frequency to be used will depend on the type of test that is being used and metric of interest (McMaster et al., 2014). Some researchers have recommended to use at least 1000 Hz for jumping protocols, particularly when measuring time-dependent variables (McMaster et al., 2014; Street et al., 2001; Owen et al., 2014). Different criteria have been applied for determining the beginning of a jump, with no general agreement as to what should be used (Eagles et al., 2015; Perez-Castilla et al., 2019c).

One of the limitations is the high cost of force plates which limits their applicability in practical settings, so they may not be widely available for athlete or clinical assessments. However, lower-cost uniaxial systems have been developed that may be more affordable and have adequate utility for power assessment (Major et al., 1998; Raymond et al., 2018).

Linear Position Transducers

Linear position transducers can be used to measure displacement and velocity and estimate power (Harris et al., 2010). Many studies have been conducted using linear position transducers for assessment of power in different populations (Harris et al., 2010; Cormie et al., 2007c; Loturco et al., 2019). Reliability of these methods has also been studied extensively (Garcia-Ramos et al., 2016; Perez-Castilla et al., 2019a; Perez-Castilla et al., 2017; Orange et al., 2018b; Askow et al., 2018; Cronin et al., 2004; Hansen et al., 2011a; Dorrell et al., 2019). The validity of linear position transducers has received much attention from researchers (Appleby et al., 2018; Askow et al., 2018; Perez-Castilla et al., 2017; Banyard et al., 2017; Drinkwater et al., 2007; Goldsmith et al., 2019; Garnacho-Castano et al., 2015; Crewther et al., 2011; Dorrell et al., 2019). These methods are more appropriate for the measurement of variables such as velocity and displacement (Perez-Castilla et al., 2019a; Garnacho-Castano et al., 2015).

Combined methods which integrate force plate and other technology, such as linear position transducers, can be used to measure power (Dugan et al., 2004). Theoretically, measuring displacement via the linear position transducer allows for direct integration of the displacement–time data. Recently this combined approach has been questioned in the literature (Mundy et al., 2016; Lake et al., 2012). Studies that compare single-method and combined-method approaches consistently show that they produce different results (Mundy et al., 2016; Hori et al., 2007; Hansen et al., 2011b). One study compared four different methods during the hang power clean and weighted jump squat exercises (Hori et al., 2007). Results were different for peak and mean power depending upon the method used (Hori et al., 2007).

Linear position transducer placement is an additional consideration for testing. One of the limitations with the technology is that it may fail to consider horizontal displacement of the barbell in exercises such as Olympic lifts. It is has been proposed to use two linear position transducers when testing these types of exercises (Cormie et al., 2007c). Studies have investigated different setups with linear position transducers for testing power (Cormie et al., 2007c). One study investigated six different configurations of two linear position transducers and force plates when testing the squat, jump squat and power clean (Cormie et al., 2007c). These included using one or two linear position transducers. The results showed clear differences in variables depending on the setup and analysis that was used. The increased accuracy of these setups needs to be balanced with additional processing and units that would be required. Therefore, it may be less appropriate for applied settings.

Contact Mats and Timing Devices

Contact mats and other timing devices can be used to estimate jump height from flight time (Dobbin et al., 2017; Kenny et al., 2012; Pueo et al., 2018; Rantalainen et al., 2018b). This can provide an estimation of other variables such as power. Due the relative low cost of these systems compared to force plates, researchers have studied their validity in a range of populations (Dobbin et al., 2017; Kenny et al., 2012; Tenelsen et al., 2019).

Photocell-based systems can also be used effectively to analyse force–velocity capabilities from estimation of ground contact time (Attia et al., 2017; Glatthorn et al., 2011; Giroux et al., 2016; Magrum et al., 2018; Castagna et al., 2013). Studies have compared these technologies with gold standard force plate systems and have found acceptable levels of validity, although ground contact time does appear to be overestimated (Magrum et al., 2018).

Computation Methods

Computation methods have been developed to measure force, velocity and power during jumping (Samozino et al., 2008; Jimenez-Reyes et al., 2017). The method utilises body mass, jump height and push-off distance (Samozino et al., 2008; Samozino et al., 2014). Originally the method was validated against a force plate using the SJ (Samozino et al., 2008). Additional studies have investigated the method in a range of populations (Giroux et al., 2015), and it can also be used with the CMJ (Jimenez-Reyes et al., 2017). The approach has also been applied to upper body movements such as the bench press (Rahmani et al., 2018). These computation methods do not require force plates with jump height able to be calculated from technology such as a contact mat. The method therefore has good application for field-based testing of groups of athletes.

Apps

Apps have been developed that allow for measurement of jump height and force–velocity aspects of resistance training performance (Balsalobre-Fernandez et al., 2015; Stanton et al., 2015; Gallardo-Fuentes et al., 2016; Driller et al., 2017; Carlos-Vivas et al., 2018; Stanton et al., 2017; Rogers et al., 2019). The apps use the camera and/or accelerometer in the device (e.g. smartphone) to perform the necessary calculations. Research has indicated that these apps can be reliable and valid across a range of tests and populations, including older adults (Cruvinel-Cabral et al., 2018; Haynes et al., 2019) and youth athletes (Rogers et al., 2019). The majority of studies have investigated within-session reliability (Balsalobre-Fernandez et al., 2015; Driller et al., 2017; Carlos-Vivas et al., 2018; Haynes et al., 2019; Stanton et al., 2017), with only limited studies measuring reliability over repeated sessions (Gallardo-Fuentes et al., 2016; Rogers et al., 2019). Reliability of jump height is excellent but further research is needed to confirm the reliability of these approaches for determining power and across a range of different assessments (Sharp et al., 2019). As smartphone technology improves and devices can sample at higher frame rates, these applications will no doubt become more widely used.

Pneumatic Measurement Systems

Pneumatic systems have been developed to measure muscle power, particularly in clinical populations (Bassey and Short, 1990; Callahan et al., 2007). These systems have demonstrated acceptable reliability for testing muscular power in older adults (Callahan et al., 2007; Bassey and Short, 1990).

Accelerometers and Wearable Sensors

With advancements in technology, wearable sensors that integrate accelerometers have been developed that can be used to measure power-related variables. Due to the lower comparative cost of these systems compared to other methods they have become more popular with practitioners. Researchers have studied these sensors to determine the reliability and validity (Orange et al., 2018a; Banyard et al., 2017; Balsalobre-Fernandez et al., 2016; Balsalobre-Fernandez et al., 2017; Lake et al., 2018a; Rantalainen et al., 2018a; Rantalainen et al., 2018b; Brooks et al., 2018; Sato et al., 2012). As with other systems, the reliability and validity varies depending on the exercise and loading (Orange et al., 2018a). As load increases, the reliability tends to become less robust (Orange et al., 2018a) which is similar to what has been found with linear position transducers (Carroll et al., 2017). Ideally researchers and practitioners can establish the reliability and validity of these systems specific to the population and conditions they are working with.

Comparison of Methods

As with the methods discussed in Chapters 4 and 5, researchers and practitioners need to recognise that different technology and analysis methods for power assessment will give different results. Many studies have been conducted comparing these different technologies (Fernandes et al., 2018a; Perez-Castilla et al., 2019d; Hori et al., 2007; Rago et al., 2018; Buckthorpe et al., 2012; Mitter et al., 2019). Studies have consistently revealed differences in power and velocity variables depending on the technology that is used (Perez-Castilla et al., 2019d; Perez-Castilla et al., 2019b). Perez-Castilla et al. (2019b) compared seven different devices during concentric-only bench press performed on a Smith machine across a range of loads (45–85% 1RM). The reliability (CV and ICC) of mean velocity varied depending on which device was used. Buckthorpe et al. (2012) compared the validity of jump height measurement in four different devices (portable force plate, belt mat, Vertec and contact mat) against a criterion force plate. The portable force plate and belt mat were found to produce the most similar results to the gold standard measurement. Mitter et al. (2019) compared the peak and mean velocity of four different devices (Push, GymAware, FitroDyne and Beast Sensor) against three-dimensional motion analysis across three different exercises (squat, bench press, deadlift) in powerlifters. The linear position transducer (Gymware) was shown to be the most valid method, with higher levels of variability also seen in the other methods. The degree of variability also depended on the exercise (Mitter et al., 2019). Another study compared five different devices measuring mean velocity, mean propulsive velocity and peak velocity in the bench press, squat and bench-pull exercises (Courel-Ibanez et al., 2019). The results also showed differences in reliability and ability to detect meaningful change between the devices. It is worth noting that many of these studies have been conducted with Smith machine devices with a fixed path so the findings may not be directly transferable to other free-weight versions of the exercises.

TABLE 6.2 Summary of common approaches used to measure power

Method	*Uses*	*Advantages*	*Limitations*
Force plate	Measure force, power and velocity characteristics of movement	Gold standard measure Reliable Valid	Expensive Less portable compared to other methods
Linear position transducers	Measure of velocity and displacement	Portable for field-based assessment Reliable Real-time feedback	Errors can result for movements that include horizontal displacement
Combined method	Measure force, power and velocity characteristics of movement	Reliable	Errors can result when bar(bell) is used to represent centre of mass
Contact mats and timing devices	Measure jump height (estimated from flight time), contact time and flight time	Portable for field-based assessment Reliable Real-time feedback	Potential for overestimation of flight time
Computation method	Measure force–velocity profiles	Can be conducted in the field Reliable	Requires additional measures of body mass, jump height and push-off distance
Apps	Measure jump height (estimated from flight time) and force–velocity profiles	Lower cost compared to other methods Portable for field-based assessment	Requires additional information to be added so can be less time efficient
Accelerometers and wearable sensors	Measure jump height, velocity and power	Lower cost compared to other methods Portable for field-based assessment Real-time feedback Reliable	Potential for overestimation of jump height

Any method that is used will have inherent limitations and assumptions which can impact the results (Hatze, 1998). Using technology that directly measures the variable of interest is preferable. For example, measuring displacement can be done with a linear position transducer. This is due the additional error associated with extra processing that needs to occur.

Table 6.2 shows a summary of the different approaches that can be used to measure power-related variables with their advantages and disadvantages.

Conclusion

Power is a fundamental aspect of performance in a range of populations. The nature of power and how it contributes to human performance is a critical consideration for researchers and practitioners. A good understanding of the different aspects of power and terminology are vital for testing. Different technologies and methods are available for the assessment of power. The different approaches have advantages and disadvantages which should be considered when assessing power.

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7

TESTING POWER

Jump Testing

Vertical Jumping

Vertical jumping is a common test used to measure lower body performance characteristics. The Sargeant test (vertical jump) was proposed as a test of athletic performance in the early 20th century (McCloy, 1932; Sargent, 1924) and has continued to be widely used in athlete assessment. One of the most widely used tests now is the CMJ, which involves the person performing a rapid vertical jump for maximum height, often with hands on hips.

Stretch-shortening cycle (SSC) performance is a common component of testing protocols for athletes (Suchomel et al., 2016; McGuigan et al., 2013; McMaster et al., 2014; McMaster et al., 2016). CMJ testing can be used to assess SSC performance with jump height higher with eccentric utilisation (Bobbert et al., 1996; Komi and Bosco, 1978) compared to SJ where the jump is performed without a countermovement. The SJ test is another common test used to measure concentric-only aspects of performance. Different methods have been used to compare CMJ and SJ performance (Suchomel et al., 2016). One method calculates the percent difference between the two tests, also known as the prestretch augmentation percentage (Walshe et al., 1996). The ratio of those tests has led researchers to suggest that eccentric utilisation ratio (EUR) is a useful measure for testing aspects of SSC performance (McGuigan et al., 2006). Table 7.1 outlines different measures that can be obtained using jump assessments. Suchomel and colleagues (2016) compared different methods for the assessment of SSC utilisation in 86 college athletes from six different sports. Little difference existed between the methods tested, including EUR and prestretch augmentation percentage.

TABLE 7.1 Summary of countermovement jump (CMJ), static jump (SJ) and reactive strength measures

Measure	*Calculation*
Eccentric utilisation ratio (EUR)	CMJ/SJ
Prestretch augmentation percentage	(CMJ − SJ)/SJ × 100
Reactive strength calculation	CMJ − SJ
Reactive strength index (RSI)	Flight time (or jump height)/contact time
Reactive strength index modified	Flight time (or jump height)/time to takeoff
Flight time-to-contraction time	Flight time/contraction time

Countermovement Jump Protocols

CMJ testing for jump height has excellent reliability (Markovic et al., 2004; Slinde et al., 2008). Many other variables have been tested and generally have very good reliability, although this is impacted by population, equipment and analysis method used (Hori et al., 2009; Cronin et al., 2004; Meylan et al., 2012; Hebert-Losier and Beaven, 2014; Heishman et al., 2018; Ditroilo et al., 2011a; Cormack et al., 2008; Sattler et al., 2012; Nuzzo et al., 2011). Limited amounts of familiarisation is required for CMJ testing, particularly with athletes (Nibali et al., 2015). Nibali et al. (2015) showed high levels of reliability in a range of CMJ variables in 113 high school athletes, 30 college athletes and 35 professional athletes.

Prior to commencing CMJ testing (or any jump assessment), a warm-up should be performed. The warm-up does not need to be extensive and can consist of body weight exercises (e.g. squats, lunges, walking Romanian deadlifts) along with some dynamic stretching. Several submaximal jumps should also be performed prior to the testing.

Instructions have been shown to be vital during jump testing (Talpey et al., 2016; Kerschner et al., 2019). In a study by Talpey and colleagues (2016), instructions were provided to either jump as high as possible or to "extend the legs as fast as possible to maximise explosive force". Instructions to jump as high and possible resulted in greater increases in jump height and peak velocity, whereas the second set of instructions maximised peak force. Kershner et al. (2019) showed differences in CMJ variables in baseball athletes depending upon whether instructions with an external (push away from the ground as explosively as possible) or internal (extending knees and hips as explosively possible) focus were used. In another study, greater kinetic variables were found during the propulsive phase of the jump with instructions to jump as fast as possible (Perez-Castilla et al., 2019b). Therefore, researchers and practitioners need to take instructions into account when performing jump testing.

When testing the CMJ, it is critical to consider the specific technical aspects that will be adhered to. Jumping with or without the use of the arms will impact on the results, with vertical jump height higher when using the arms (Hara et al., 2006; Harman et al., 1990; Slinde et al., 2008; Lees et al., 2004; Mosier et al., 2019). For example, a study by Mosier et al. (2019) showed a 13.6% increase in vertical jump height when using arm swing compared to no arm swing in recreationally trained men. Reliability does not appear to differ whether arm swing is used or not (Slinde et al., 2008; Heishman et al., 2018; Markovic et al., 2004). It has also been demonstrated that different arm swing techniques can affect vertical jump mechanics, but not jump height (Gutierrez-Davila et al., 2014). Specific jump tests that utilise arm swing may be appropriate for certain sports (e.g. volleyball) and could increase the specificity of the test (Mentiplay et al., 2015; Muehlbauer et al., 2017; Mosier et al., 2019). The Abalakov jump has been described as jumping with a tape measure attached to a belt and can be performed with jumping using the arms (Markovic et al., 2004). If flight time is being used to estimate jump performance, then attention needs to be paid to technique. Flight time can be artificially inflated by allowing the participant to lift their legs during the jump.

The depth of the countermovement is another testing consideration (Gheller et al., 2015; Bobbert et al., 2008; Domire and Challis, 2007; McBride et al., 2010; Mandic et al., 2015; Perez-Castilla et al., 2019b). For CMJ testing, kinetic and kinematic variables may differ depending on the starting angle of the countermovement (Gheller et al., 2015; McBride et al., 2010; Perez-Castilla et al., 2019b). For example, McBride and colleagues (2010) showed that vertical impulse, peak power, peak force and jump height did vary, depending upon the squat depth during CMJ. Based on the available evidence, practitioners can use self-selected depth of the countermovement when assessing jump height (Mandic et al., 2015; Domire and Challis, 2007). However, depth of the countermovement does need to be considered when measuring other force and power variables (McBride et al., 2010; Perez-Castilla et al., 2019b).

Several trials should be conducted with jump assessments. Testing could be conducted using single or multiple (but fewer than five) efforts (Cormack et al., 2008). Completing several trials within the testing session can help reduce the variability of high-intensity testing (Haugen and Buchheit, 2016). Only limited rest periods (< 1 minute) are required between trials (Nibali et al., 2013a).

Another consideration is whether to use average of multiple trials or the best value (Al Haddad et al., 2015). Ultimately, this will depend upon the variable of interest and the purpose of testing. Claudino and colleagues (2017) showed that using average CMJ height was more sensitive than peak CMJ height for monitoring neuromuscular fatigue. Other research suggests that either approach is valid when being used for testing jump performance (Al Haddad et al., 2015).

Squat Jump Protocols

The SJ test is used to assess concentric-only jump performance. SJ assessments (referred to as either squat or static jumps) have also been shown to be highly reliable (Markovic et al., 2004; Petronijevic et al., 2018; Hebert-Losier and Beaven, 2014; Cronin et al., 2004; Sattler et al., 2012). As is with the case with CMJ testing, limited familiarisation is required with trained adult populations (Moir et al., 2005).

The test begins in a set squat position that is held for 2–3 seconds. One of the issues with the SJ test is controlling the small amplitude countermovement that can occur at the start of the jump (Sheppard and Doyle, 2008). A set position of 90° has been used to standardise the testing protocol. However, self-selected depth appears to be valid for SJ testing (Mitchell et al., 2017; Petronijevic et al., 2018; Fitzgerald et al., 2018; McBride et al., 2010; Janicijevic et al., 2019). Petronijevic and colleagues (2018) compared self-selected and standardised starting positions for SJ testing in handball players and physical education students. No differences were found between the protocols for the jump variables, and both protocols were highly reliable. However, as with CMJ testing, McBride et al. (2010) showed meaningful differences between peak power, vertical impulse, peak force and jump height in SJ testing across loads (bodyweight, 20%, 40% 1RM).

For both CMJ and SJ testing performed on a force plate, the start of the movement needs to be detected (Meylan et al., 2011). Different approaches have been suggested for detecting jump onset that use absolute or relative thresholds (Meylan et al., 2011; Giroux et al., 2015; Owen et al., 2014). A study compared the reliability and magnitude of results during loaded and unloaded SJs (Perez-Castilla et al., 2019a). Five different starting thresholds were compared where vertical ground reaction force exceeded the system weight by 10 N, 50 N, 1% of system weight, 5% of system weight and five standard deviations of system mass minus 30 msec. Reliability was higher under more conservative conditions (50 N, 5% of system weight and five SDs). The magnitude of the variables also varied across the different conditions (Perez-Castilla et al., 2019a). Based on current evidence, there is no general agreement on which starting threshold to use (Eagles et al., 2015). The accuracy of testing, particularly when being performed on a force platform will be enhanced by having the individual stay as still as possible prior to initiation of the test.

Jump testing can be conducted bilaterally or unilaterally. With dual-force plate systems, it is possible to also detect bilateral asymmetries with these tests (Patterson et al., 2009). The different analysis methods that can be used for measurement of asymmetries are discussed in Chapter 9.

Horizontal Jumping

While vertical assessment provides critical information on SSC characteristics, horizontal testing is also a valuable test, with the broad jump test a mainstay of testing batteries for many years (Hardy et al., 2018). It has also been demonstrated to be reliable for the majority of variables (Markovic et al., 2004; Hebert-Losier and Beaven, 2014; Meylan et al., 2012). Given the importance of horizontal force production during activities such as sprinting, it could be argued that this component should be tested as a priority over vertical aspects. However, both aspects have been shown to be important during sporting activities such as sprinting and can provide valuable information (Loturco et al., 2015; Jimenez-Reyes et al., 2018; Haugen et al., 2019).

Studies have investigated the relationship between horizontal and vertical aspects of jump performance demonstrating that the assessments provide unique information (Meylan et al., 2010; Dobbs et al., 2015; Bishop et al., 2018). The tests can also be used to assess bilateral or unilateral performance (Bishop et al., 2017; Dobbs et al., 2015; Meylan et al., 2009).

Horizontal Jumping Protocols

Instructions also need consideration with broad jump testing. For example, research has shown increased broad jump performance using an external focus of attention (Porter et al., 2012; Porter et al., 2010). As with the other jump assessments, participants need to be adequately warmed up for testing. More familiarisation may be required with broad jumping, particularly with individuals unfamiliar with the task. Evidence has shown greater variability in younger children with this test, particularly with the eccentric variables (Meylan et al., 2012). Practitioners should also be aware of the higher intensity associated with this type of testing, compared to vertical movements (Wallace et al., 2010). Therefore, inexperienced jumpers may experience greater amounts of DOMS following this testing.

Reactive Strength Assessment

Drop jump testing can be used to measure reactive strength and ability to tolerate rapid SSC movements. The reactive strength index (RSI) is a common measure that is used (Flanagan et al., 2008; Markwick et al., 2015). This can be calculated in several ways (Table 7.1). The measure can be expressed as contact time relative to flight time (or jump height) which requires some type of measurement device. A single jump height can be used, for example, 45 cm, or a profile of several heights used, such as 40, 60 and 80 cm (Moir et al., 2018b; Walshe and Wilson, 1997; Tenelsen et al., 2019). Using several heights allows stretch tolerance to be examined with increasing degrees of SSC. Looking at landing characteristics such as contact time and landing forces can also provide vital information (Bobbert et al., 1987; Bates et al., 2013; Lake et al., 2018; Janssen et al., 2012).

The modified RSI determined from a standard vertical jump has also been proposed (Kipp et al., 2016; Suchomel et al., 2015a, 2015b; Ebben and Petushek, 2010). This is calculated using jump height and time to takeoff (Ebben and Petushek, 2010). The flight time-to-contraction time ratio has also been used for athlete assessment (Cormack et al., 2008). The flight time-to-contraction time ratio been shown to provide the same information as the modified RSI

(McMahon et al., 2018). Whichever method is chosen, it should be used consistently, and practitioners need to be aware of differences that may exist with other approaches. The reliability of these variables has been shown to be acceptable (Flanagan et al., 2008; Markwick et al., 2015; Haynes et al., 2019).

Drop Jump Protocols

Of all the jump assessments, instructions are the most important with drop jump testing (Khuu et al., 2015). A common instruction is "step out from the box" and "jump as high and fast as possible". Also reminding the participant to think of the force plate/contact mat as a "hot plate" can be a useful cue for minimising contact time. Due to the increased technical demands of this test, participants may require more familiarisation. Only very short rest periods are required between trials (Read and Cisar, 2001). Also, testing can be conducted bilaterally or unilaterally.

Load–Velocity Profiling

The effect of load on power and velocity characteristics is commonly used in athlete assessment (Moir et al., 2018b; Sheppard et al., 2008; Young, 1995; Loturco et al., 2019; McMaster et al., 2016; Nibali et al., 2013b). For example, reliability of power–load and velocity–load isoinertial assessments have been demonstrated in bench press and squat exercises (Pallares et al., 2014; Hansen et al., 2011).

Ballistic exercises can be used for assessment of power variables during these movements (Newton et al., 1997). Bench press throws and jumps squats are common exercises used in athlete assessment. Performing these movements ballistically helps reduce the influence of the deceleration phase. Many studies have compared ballistic and non-ballistic versions of these exercises, including the bench press (Moir et al., 2018a; Clark et al., 2008; Loturco et al., 2018; Pestana-Melero et al., 2018) and squats (McBride et al., 2011; Suchomel et al., 2018). Rotational movements have also been investigated across a range of loads to determine their velocity capacities (Schofield et al., 2019a).

Load–Velocity Profile Protocols

Different approaches have been used for load–velocity profiling. One method is to use absolute load for exercises such as bench press throws (e.g. 40–80 kg) (Baker and Newton, 2006) or relative load as a percentage of 1RM (e.g. 15–75% 1RM) (McMaster et al., 2016). A similar method has been used with jump squats with absolute loads such as 40 kg (McGuigan et al., 2009; Fernandes et al., 2019), an incremental profile with load expressed relative to bodyweight (Sheppard et al., 2008; Alcazar et al., 2017; Patterson et al., 2009) or as a percentage of 1RM (Cormie et al., 2007). For example, Patterson et al. (2009) documented the loaded SJ profile used with Austrian alpine ski team as 0, 25, 50, 75, and 100%

of bodyweight added to a bar. These concepts have also been applied with other exercises such as push press (Lake et al., 2014) and leg press (Padulo et al., 2017).

With the addition of load for jump profiling, researchers and practitioners can still use short periods between trials without significant impact on the results (Nibali et al., 2013a). Force–velocity profiling can also be used with older adults and clinical populations (Alcazar et al., 2017; Alcazar et al., 2018c). Alcazar and colleagues (2017) investigated the efficacy of force–velocity profiling using leg press in 31 older men and women (mean age = 75.8 ± 4.7 years). The three-load method was found to be reliable when using mean velocity. Importantly, very few reports of adverse events have been made with this type of testing in clinical populations (Alcazar et al., 2018a). An interesting question is how many loads need to be used for profiling. Two loads appear to be the minimum for force–velocity profiling (Moir et al., 2018b; Jaric, 2016). It may be preferable to use more than two loads but practitioners would need to consider the added value using this approach in relation to the added time needed for testing.

Concerns over excessive loading and impact forces associated with ballistic jumps should be considered with these tests (Lake et al., 2018; Janssen et al., 2012). Various systems have been developed to help reduce the impact forces during loaded jumping (Humphries et al., 1995). Research has shown increased landing forces with more load during CMJ testing (Lake et al., 2018). Instructions should be given to participants that encourage them to effectively absorb forces during landing. Research has shown that different participants can effectively achieve this after instruction (Milner et al., 2012; Prapavessis et al., 2003).

Upper Body Assessment

Like vertical jump testing, the principle of comparing SSC movements to concentric-only tasks can be applied. For example, the bench press can be tested in this manner with ballistic bench throws with and without SSC utilisation (Perez-Castilla et al., 2018; Newton et al., 1997; Cronin et al., 2003; Moir et al., 2018a). The ballistic or plyometric push-up has been investigated as an upper body power assessment (Bartolomei et al., 2018; Wang et al., 2017; Gillen et al., 2018; Hogarth et al., 2014; Zalleg et al., 2018; Dhahbi et al., 2017). Gillen and colleagues (2018) reported the reliability and sensitivity of plyometric push-ups performed on a force plate in 68 youth athletes aged 6–15 years. Very few variables were reliable or sensitive, although peak force and peak RFD approached acceptable reliability for those aged 12–15 years (ICC > 0.8). This is in agreement with earlier research that suggests that the test is not of sufficient reliability in athlete populations for most variables (Hogarth et al., 2014). One of the challenges with the test is controlling the range of motion of the push-up. Researchers have also shown that the hand position at the start of the test can have an impact on height, peak power, peak force and peak rate of power development (Nichols and Szivak, 2019). The plyometric push up test has also been investigated as a predictor of 1RM bench press (Bartolomei et al., 2018). While there was an association between the tests, the plyometric push-up overestimated 1RM bench press significantly (Bartolomei et al., 2018). Several variations of the test are available (Zalleg et al., 2018; Dhahbi et al., 2017), but based on current evidence the assessment should be used with caution due to the low reliability of most variables.

Performance tests such as the seated medicine ball throw can be a useful test for the assessment of upper body power (Harris et al., 2011). The backward overhead medicine ball throw test has also been investigated (Mayhew et al., 2005). Variations of these tests have been used by track and field coaches for many years. New variations of the test continue to be studied by researchers such as the medicine ball push press (Sayers and Bishop, 2017).

Sport-specific upper body power tests have also been developed and tested for a range of populations (Laffaye et al., 2014; Draper et al., 2011; Lawton et al., 2013; Pearson et al., 2009; Pearson et al., 2007). Laffaye et al. (2014) tested the validity and reliability of a climbing power test that could be used to profile rock climbers. The test used an isoinertial accelerometer and compared performance in novice, skilled and elite climbers. Ergometers have been used to measure power for sports such as rowing (Lawton et al., 2013) and kayak (Borges et al., 2017). As with lower body power tests, verbal feedback can have an impact on upper body power variables and should be standardised (Argus et al., 2011).

Stiffness

Stiffness is a measure that is often used as a component of power assessment (Brazier et al., 2017; Brughelli and Cronin, 2008). Stiffness refers to the relationship between the structure of a system and the degree of deformation that occurs. It consists of several aspects which can include joint stiffness, vertical stiffness and leg stiffness (Brazier et al., 2017). Stiffness is considered important due to its relationship with athlete performance and injury risk (Pruyn et al., 2012; Pickering Rodriguez et al., 2017). It has also been shown to differentiate athletes from different sports when performing specific tasks such as sprinting, change of direction and hopping (Millett et al., 2018).

Laboratory-based tests such as the free oscillation technique have been used by researchers to measure stiffness (Wilson et al., 1994; Walshe et al., 1996; Ditroilo et al., 2011c). A recent study showed poor reliability for this method applied to the bench press, bench row and back squat exercises across a range of loads (Schofield et al., 2019b). This is similar to findings by other researchers who have applied this method to knee flexor and extensor tests (Ditroilo et al., 2011b). Simple field tests have been developed which can measure aspects of stiffness (Dalleau et al., 2004; Walshe et al., 1996; Pruyn et al., 2016; Maloney et al., 2015). The method developed by Dalleau et al. (2004) forms the basis of many jump-based protocols. In their work, a jump mat was used to provide reliable and valid measures of vertical and leg stiffness in a repeat hopping test (Dalleau et al., 2004).

Drop jump tasks are also used to measure stiffness (Maloney et al., 2015). Typically, these tests require force plates to accurately assess stiffness although attempts have been made to use other methods. For example, linear position transducers have been used to assess musculoskeletal stiffness during upper body movements (Hernandez-Davo et al., 2018). A method developed by Hernandez-Davo et al. (2018) used the barbell velocity measured during the final 50 msec of the eccentric phase to estimate vertical stiffness.

Other Power Tests

Testing older adults and clinical populations can be challenging due to physical impairments that may limit the feasibility of certain power assessments. Performance tests such as the sit-to-stand test may provide useful insights into power characteristics (Alcazar et al., 2018b; Orange et al., 2019; Csuka and McCarty, 1985). The sit-to-stand test is a timed assessment that requires the person to stand from the seated position for a set number of repetitions (Csuka and McCarty, 1985). Five repetitions are commonly used for this assessment (Churchward-Venne et al., 2015; Bohannon, 2011). Alcazar and colleagues (2018b) showed strong relationships between estimated power during the sit-to-stand test and leg press force–velocity characteristics. Orange et al. (2019) measured power using an inertial sensor during the sit-to-stand test in 38 adults. The results showed power generated during the test to be strongly related to other functional tests. Mean velocity during a chair squat, as measured via a smartphone app, has been demonstrated to be related to functional status in older adults (n = 40, mean age 72.2 ± 4.9 years) (Balsalobre-Fernandez et al., 2018). While these tests can provide useful information, all the assessments discussed in this chapter could be effectively modified to measure power-related qualities in different populations.

Conclusion

Many assessments are available for the assessment of power. Practitioners can use CMJ, SJ, depth jumps, load–velocity profiling and various upper body assessments to measure power characteristics. The tests can be used in a range of populations, from older adults to youth athletes. As with all assessments, consideration should be given to establishing reliable and valid protocols, what equipment will be used, analysis of the data and how the information can be used to inform training programmes.

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8

TESTING STRENGTH AND POWER ENDURANCE

Importance of Strength and Power Endurance

Strength and power endurance are important qualities for a range of sports. Sports that involve cyclic activities of repeated high-intensity efforts rely on strength and power endurance. This includes sports such as rowing, kayaking and skiing. Many sports, such as basketball and volleyball, also involve repeat efforts for tasks such as jumping. Team sports require participants to repeat different high-intensity efforts such as sprinting, accelerations, decelerations and change of direction tasks. Muscular endurance qualities have been shown to be important for specific tasks such as tackling in rugby league players (Gabbett and Wheeler, 2015). Several assessments are available for assessment of strength and power endurance (Patton and Duggan, 1987) and will be outlined in this chapter. Muscular endurance assessments are often used with tactical populations such as the military and police (Fielitz et al., 2016; Marins et al., 2019; Naclerio et al., 2009; Bloodgood et al., 2019).

In addition to being important for certain sports, strength and power endurance has also been demonstrated to be critical for health outcomes in a range of populations (Roshanravan et al., 2017; Vaara et al., 2012). Muscular endurance (as measured using total work over a repeat effort test) was associated with mobility and mortality in a cohort of 1963 older adults (Roshanravan et al., 2017). Vaara and colleagues (2012) investigated associations between muscular endurance and strength with body composition and cardiorespiratory fitness in 846 men. Muscular endurance was most strongly associated with cardiorespiratory fitness and body composition. Bodyweight muscular endurance tests are relatively easy to perform and can be used with large groups; thus, they can be appealing as an assessment. Therefore, strength and power endurance assessments can have broad application with many groups. However, it is also important to consider the impact of external load on strength and power endurance as this may be more specific for certain sports.

What is clear from the research is that strength, power and muscular endurance are distinct qualities (Naclerio et al., 2009). While these capacities are related, they do represent separate qualities. As such, if the needs analysis of the individual, sport or event identifies that strength or power endurance is important, then specific tests for assessment of that quality can be considered. Several types of assessments have been developed by researchers, with a focus on reliability and validity.

Muscular Endurance Testing

Traditionally, muscular endurance has been defined as a measure of the capacity to perform repeated contractions with a given load or exerting force for an extended period (Lawton et al., 2013). The fact that more repetitions can be performed as loads are decreased is well established (Jevons, 1870). Testing can occur by measuring the number of repetitions that can be performed with an absolute load such as bodyweight. A common test for upper body muscular endurance has been the push-up test (Wood and Baumgartner, 2004; Baumgartner et al., 2002; Mayhew et al., 1991). The sit-up test is another commonly used muscular endurance test (Bianco et al., 2015; Berger, 1966; Barnekow-Bergkvist et al., 1996; Tomkinson et al., 2018). Different approaches have been used, including the maximum number of sit-ups or push-ups that can be performed (Baumgartner et al., 2002; Barnekow-Bergkvist et al., 1996) or the maximum number within a certain time period (e.g. 30 seconds to 2 minutes) (Fielitz et al., 2016; Mayhew et al., 1991; Berger, 1966; Gabbett et al., 2008; Invergo et al., 1991; Tomkinson et al., 2018). The reliability of muscular endurance tests has been previously reported (Gabbett et al., 2008; Mayhew et al., 1991; Fielitz et al., 2016; Negrete et al., 2010). For example, Gabbett and colleagues (2008) showed high reliability for timed (60 seconds) push-up (ICC = 0.94, CV = 7.3%) and sit-up testing (ICC = 0.90, CV = 7.9%) in junior rugby league players.

The advantage of these tests is that they require no additional equipment and it is possible to test large groups efficiently. As with the plyometric push-up (Chapter 7), the technique needs to be highly standardised to increase reliability and validity. The hand position can have a significant impact on the results, along with other technical aspects (Baumgartner et al., 2002). Different testers need to be educated on the correct technique and how to score the test correctly to ensure interrater reliability (Fielitz et al., 2016). It is also important to note that while there is an association between muscular endurance and strength (Vaara et al., 2012; Naclerio et al., 2009), these assessments cannot be used as a surrogate for maximal strength testing (Mayhew et al., 1991).

Muscular endurance can also be assessed with free weight and machine exercises. One approach is to measure the number of repetitions that can be performed with a relative load (Desgorces et al., 2010). For example, the test could be performed with 60% of 1RM (Campos et al., 2002; Cholewa et al., 2019) or 70% of 1RM (Volek et al., 2003) on exercises such as squats, bench press or deadlift. Another method has been to use a percentage of the participant's bodyweight (Thomas et al., 2015). For example, Thomas and colleagues (2015) used lat pulldown and chest press machine exercises with 30% of the participant's bodyweight to measure muscular endurance in 212 sedentary individuals.

The pull-up test is another common muscular endurance test (Beckham et al., 2018; Halet et al., 2009; Lombard et al., 2015; Gabbett et al., 2008; Daniels et al., 2019; Gabbett and Wheeler, 2015). However, its classification as a strength endurance test depends on the individual being tested being able to perform at least a single pull-up with their bodyweight. The pull-up test has been shown to be reliable in junior rugby league players with reported ICC = 0.98 and CV = 6.4% (Gabbett et al., 2008).

Muscular endurance can be assessed with isometric actions (Salmon et al., 2015). Different joints have been used with these assessments. For example, the ability to sustain a level of force can be measured and the decrement over time calculated. The flexed arm hang test (pull-up position) can be used in this manner (Tomkinson et al., 2018). The test involves timing how long an individual can hold the fixed isometric position with a pronated grip. However, research has not shown acceptable validity for its testing of muscular endurance in that it represents more of a measure of relative isometric strength (Clemons, 2014; Clemons et al., 2004). Other tests that involve holding isometric positions include the Biering-Sorenson test (Latimer et al., 1999; Juan-Recio et al., 2018; Westerstahl et al., 2018) and other trunk extension tests (Vera-Garcia et al., 2019; McGill et al., 1999). Different assessments have been used that measure the ability to hold these positions for maximum time (McGill et al., 1999). Most of these tests have demonstrated good reliability (Latimer et al., 1999; McGill et al., 1999). An advantage of these tests is that they require minimal equipment. However, it is important that the effect of body position during the tests is controlled (Tse et al., 2010). Tse and colleagues (2010) investigated the effect of body positioning on an abdominal flexor endurance test and Biering-Sorenson test performed by rowers. Minor adjustments in trunk posture led to increased holding times for the tests, highlighting the importance of standardizing body position during the assessment (Tse et al., 2010). Reporting of test scores and issues involving body size will be discussed in Chapter 9.

As discussed in Chapter 3, muscular endurance tests have been studied as a predictor of 1RM (Mayhew et al., 1992; Mayhew et al., 1995; Ware et al., 1995). This has been based on the relationship between muscular endurance and strength (Figure 8.1). Figure 8.1 shows an example for an individual of how many repetitions were performed at different percentages of 1RM. Note that this relationship will vary depending on the individual and exercise.

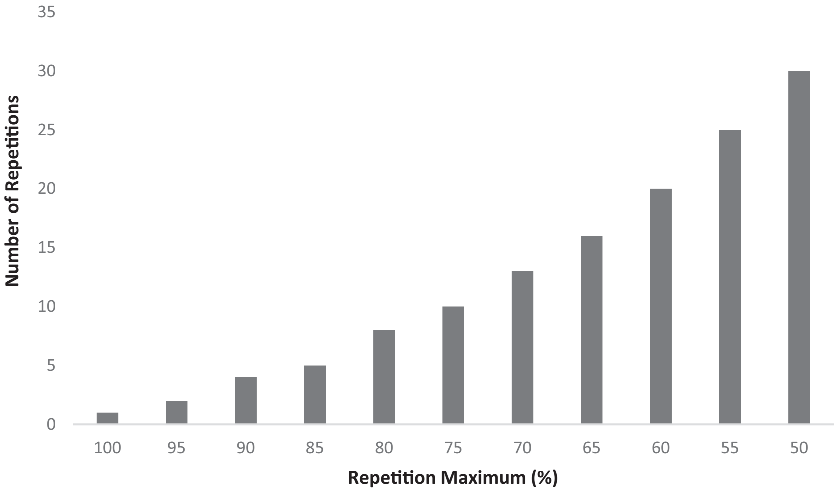

FIGURE 8.1 Relationship between strength and endurance

Isokinetic assessments have been used historically for measuring strength and power endurance in a range of populations (Pincivero et al., 1997; Roshanravan et al., 2017; Gerdle et al., 1986; Muller et al., 2007; Buford et al., 2008; Lindstrom et al., 1997; Katsiaras et al., 2005). As with any strength and power assessment, the technique must be standardised and repeatable (see Chapter 3). These aspects will increase test reliability and validity.

The concept of critical power has been applied to resistance training using the deadlift (Dinyer et al., 2019) and bench press (Morton et al., 2014). The critical resistance test measures the number of repetitions to failure across a range of intensities. For example, Dinyer and colleagues (2019) used a critical resistance test which involved performing maximum repetitions with 50, 60, 70 and 80% 1RM. Total work was calculated (sets × repetitions × displacement) and plotted against total displacement the barbell travelled. Subsequently 30 repetitions with a critical resistance (determined from the model) was tested but showed poor agreement with the model, particularly at resistances above the critical resistance.

Repeated Jump Test

Fatiguing jump and SSC protocols have been studied by researchers to further understand the mechanisms underlying power endurance. Repeated jump testing has been designed to assess repeated SSC capacities (Dal Pupo et al., 2013; McNeal et al., 2010; Kuitunen et al., 2002; Kuitunen et al., 2007; Weinhandl et al., 2011; Sands et al., 2004; Bosco et al., 1983b; Hespanhol et al., 2007). The test is particularly suited for sports which require repeat jump efforts such as volleyball, basketball and gymnastics. The 30-second Bosco test (repeated vertical jumping for 30 seconds) has been shown to induce fatigue with decreased jump performance along with altered joint kinematics and vertical stiffness (Dal Pupo et al., 2013). McNeal et al. (2010) investigated changes in kinetics and kinematics during the 60-second Bosco test in athletes. Muscle activation and flight time were reduced earlier in the jump protocol, with changes in force production and jump technique occurring later.

The traditional Bosco test consists of repeated jumps performed for a set time period of 15–60 seconds (Bosco et al., 1983b; Bosco et al., 1983a). The jumps are performed continuously and using a consistent jump depth with hands on hips. The following formula is used to calculate mean power:

$$\text{Mean power (watts)} = \text{flight time of all jumps} \times \text{test duration} \times g^2/4 \times \text{number of jumps} \times (\text{test duration} - \text{total flight time})$$

The repeated jump test has demonstrated good reliability ($r = 0.95$) (Bosco et al., 1983b). Several other studies have investigated the reliability of the Bosco test (Cular et al., 2018; Dal Pupo et al., 2014). Cular and colleagues (2018) reported good reliability for peak and mean jump height during the test (CV = 4.8–6.0%, ICC = 0.74–0.88) in youth karate athletes. However, reliability was poor for fatigue index measures (CV > 26.5%, ICC = 0.66). Dal Pupo et al. (2014) reported excellent reliability for peak and mean jump height (CV = 2.5–3.8%, ICC = 0.94–0.98), but poorer reliability for the fatigue index (CV = 10.8%, ICC = 0.87) in 21 volleyball athletes.

Comparisons have been made between repeated jump tests and Wingate tests in a range of populations (Theodorou et al., 2013; Sands et al., 2004; Cular et al., 2018; Hoffman et al., 2000; Nikolaidis et al., 2016; Dal Pupo et al., 2014). Sands et al. (2004) showed a moderate correlation between the 60-second repeat jump test and Wingate for peak power ($r = 0.69$) and mean power ($r = 0.89$). Hoffman and colleagues (2000) compared the Wingate test, 15-second repeated jump test and line drill test (continuous 143 metre running with several changes of direction) in nine basketball players. Poor relationships were found between peak power and mean power in the Wingate test and repeated jump test ($r = 0.20$–0.28). These findings were similar to Nikolaidis and colleagues (2016) who found low to moderate relationships between Wingate test mean power and Bosco test mean power ($r = 0.27$–0.54) in volleyball players. The relationship was stronger in the adult players but lower in adolescents. Overall the findings would suggest that these tests not be used interchangeably.

Repeated jump testing has been used in alpine ski athletes due to the importance of power endurance in events lasting 1–2.5 minutes (Bosco et al., 1994; Patterson et al., 2014). Bosco et al. (1994) tracked power characteristics of Italian alpine skiers using several tests, including 15–30 seconds repeated jumping. Patterson et al. (2014) described the 2.5-minute loaded repeated jump test that was used with the Austrian Alpine ski team. The test was conducted with an external load of 40% of the athlete's bodyweight, with 60 CMJ repetitions performed every 2.5 seconds. Mean power and power every 30 seconds were calculated. The reliability of the measures was high, although only ICCs were calculated (ICC = 0.881–0.987). A difference between this test and Bosco tests is the pause that occurs between repetitions which may result in greater reliability. The 2-minute loaded repeated jump test has been used with the Austrian Alpine Women's ski team (Patterson et al., 2019). The test uses a load of 20% of the athlete's bodyweight, with 48 jumps performed every 2.5 seconds.

A fatigue index can be calculated from these tests. Ideally, a baseline measure of peak performance should be determined which can be used as a reference (Patterson et al., 2019). For example, for the 2-minute loaded repeat jump test this could be calculated as follows:

> Fatigue index (%) = (peak relative power – average of relative power over final 30 seconds)/peak relative power × 100

Other Repeat Effort Protocols

A variety of other protocols have been investigated for the assessment of power endurance (Hatfield et al., 2006; Gabbett et al., 2008; Spiering et al., 2011; Alemany et al., 2005). The protocols typically involve measuring power variables while performing an exercise with fixed load for a set number of repetitions. Decrements for the metric of interest can then be calculated. For example, Hatfield and colleagues (2006) measured peak power during four sets of 12-repetition jump squats with 30% of 1RM (2 minutes rest between sets). A study by Alemany and colleagues (2005) used 30 repetitions of 30% of 1RM for jump squats and bench press throws. The reliability of both tests was high, with CVs ranging from 3.0–7.6% across the different variables. Gabbett et al. (2008) utilised a repeated 10-jump test in junior rugby league players with a Vertec. Jumps were performed every 5 seconds and the total jump height calculated across the 10 jumps (ICC = 0.89, CV = 4.5%). Spiering and colleagues (2011) used leg press performed with 40% of maximum for 21 repetitions and bench press with 30% of maximum for 21 repetitions. A fatigue index was calculated using:

> Fatigue index (%) = (highest peak power during a repetition – lowest peak power during a repetition)/highest peak power during a repetition × 100

The reliability of the fatigue index was poor, with ICC = 0.36 for leg press and ICC = 0.62 for bench press and SEM = 16–18%. Total work for the test was more reliable, with ICC = 0.99 for both tests and SEM = 4%.

Naclerio et al. (2009) utilised a maximum bench press repetition test with firefighters to investigate the relationship between muscular endurance, strength and power. The test involved performing maximum number of repetitions with

40 kg in 40 seconds, along with recording variables such as mean power with a linear position transducer (Naclerio et al., 2009). In addition, percentage change in these variables can be determined across the test.

A similar approach has been taken with isokinetic protocols (Roshanravan et al., 2017; Lindstrom et al., 1997; Katsiaras et al., 2005). For example, Katsiaras and colleagues (2005) used a 30-repetition isokinetic leg extension/flexion at 180°/sec and calculated the fatigue index as:

$$\text{Fatigue index (\%)} = (\text{final peak torque} - \text{initial peak torque}) \times 100$$

with the final peak torque being the maximum peak torque and initial peak torque the lowest peak torque. Total work was also calculated over 30 repetitions for both knee flexion and extension. Lindstrom and colleagues (1997) tested older and younger men and women using a 100-repetition leg extension test at 90°/second. Fatigue rate and relative reduction on force were calculated to enable comparisons between the groups.

The sit-to-stand chair test (Chapter 6) can also be used as a power endurance assessment. The 30-second timed test has been commonly used with older populations (Jones et al., 1999; McCarthy et al., 2004). As with other testing methods, technical aspects such as chair height do need to be considered and standardised.

Sports-Specific Tests

Sports-specific strength and power endurance tests have been developed by researchers for a range of sports (Sheppard et al., 2007; Pearson et al., 2009; Lawton et al., 2013; Lawton et al., 2014). For example, Sheppard et al. (2007) developed a repeated jump test for volleyball based on match performance analysis data. Reliability and validity were assessed after input from sports coaches; the test was found to discriminate between elite and developmental players.

Pearson and colleagues (2009) explored relationships between strength, power and endurance in America's Cup sailors. The study used a specific 8-second forward and backward grinding test. Bench press 1RM and peak force were strongly correlated with forward grinding performance ($r = 0.99$), and bench pull was strongly related to backward grinding performance ($r = 0.95$). Bench pull peak power also had a strong relationship with backward grinding performance ($r = 0.98$), but was less robust for forward grinding ($r = 0.49$–0.55).

Strength and power endurance assessments have been studied in elite rowers (Lawton et al., 2013; Lawton et al., 2014). In a study of 20 elite heavyweight rowers, various strength and endurance tests (5RM, 30RM, 60RM and 120RM) were performed on a dynamometer using leg press and pulling movements (Lawton et al., 2014). In this population only the 5RM test met suitable reliability criteria, with the other tests having CVs $> 5\%$ and ICCs < 0.90.

Other researchers have developed sports-specific upper body power endurance tests (Stoggl et al., 2007; Borve et al., 2017). Stoggl et al. (2007) investigated a two-phase double-poling test on a rollerboard with elite cross country skiers consisting of 4 maximum repetitions followed by 40 repetitions after a 3-minute rest period. Both aspects of the test were shown to be valid and reliable (Stoggl et al., 2007). Interestingly the velocity and power aspects of the test were highly reliable (CV = 1.80–2.87%). However, like other power endurance tests, the fatigue index measures tended to be less reliable (CV = 8.06–23.18%). Borve and colleagues (2017) used a double-poling test with a cable pulley setup with well-trained cross country skiers. The muscular endurance test was set at 55% 1RM, and athletes completed the maximum number of repetitions possible. To increase the specificity of the test, athletes performed the repetitions with a constant double-poling motion that had been determined from video analysis.

Bench Press Tests

The YMCA bench press test can be a test of strength endurance (Kim et al., 2002; Invergo et al., 1991; Rose and Ball, 1992; Morton et al., 2014). The test involves lifting a fixed resistance at a set cadence. The test has used 36.4 kg (80 lb) for men and 15.9 kg (35 lb) for women at a lifting cadence of 30 (Invergo et al., 1991) or 60 reps per minute (Kim et al., 2002). The test has also been modified to use 20.4 kg for women (Rose and Ball, 1992). Advantages of the test are that it only requires one absolute load and is reliable (ICC = 0.97–0.98). It has been proposed that the test can be used to accurately predict 1RM bench press in untrained individuals (Rose and Ball, 1992; Kim et al., 2002). Whether this relationship would be as robust in trained individuals has yet to be investigated. Variations of this test have been used with an absolute load performed for maximum number of repetitions (Barnekow-Bergkvist et al., 1996; Westerstahl et al., 2018). For example, Barnekow-Bergkvist and colleagues (1996) used 20 kg for men and 12 kg for women for the bench press as a muscular endurance test. To increase the reliability of the test it is important to use a metronome or timing device to maintain the pacing throughout the test.

The NFL-225 test (maximum repetitions on the bench press with 102.3 kg) has been widely used, particularly in North America due to its use in the NFL Combine (Mann et al., 2015; 2014, 2012; Chapman et al., 1998; Mayhew et al., 2002). Whether this test can be defined as a test of muscular endurance will of course depend on the strength of the individual. For example, many individuals will be unable to bench press 102.3 kg. Reliability of the test has been shown to be high (ICC = 0.99) (Mann et al., 2014). The test has also been used to estimate 1RM (Chapman et al., 1998; Mayhew et al., 2002; Mayhew et al., 1999). Mayhew and colleagues (1999) validated the NFL-225 test and found a strong correlation with 1RM bench press in 142 college football players ($R = 0.96$). The study also developed a prediction equation that could be used to estimate the 1RM bench press (provided the person can bench press at least 102 kg):

$$1\text{RM (lb)} = 226.7 + 7.1(\text{repetitions with 225 lb})$$

(to convert to kg divide by 2.2045).

As this is a multiple-repetition test, technical aspects need to be adhered to in order to maintain the validity and reliability of the test. For example, the pacing of the test needs to be maintained. Mayhew and colleagues (1999) required no more than 2 seconds between repetitions, no bouncing the weight off the chest and full extension of the arms to complete the repetition. Adhering to strict criteria will improve the reliability and validity of the test.

Squat Tests

The Kansas squat test has also been developed to measure anaerobic power in athlete populations (Fry et al., 2014; Luebbers and Fry, 2015; Luebbers and Fry, 2016). The test involves 15 back squats performed with a barbell load equating to 70% of system mass ((1RM + bodyweight) × 0.7 – bodyweight) with each repetition completed every 6 seconds (as measured by a metronome). A linear position transducer (or similar device) is used to measure variables such as peak and mean power throughout the test. Fry and colleagues (2014) tested the reliability and validity of the test in 14 resistance-trained men. The Kansas squat test was compared to the Wingate test with good validity and reliability for mean power ($R = 0.752$, ICC = 0.937) and peak power ($R = 0.775$, ICC = 0.811) but poor for relative fatigue % ($R = 0.174$, ICC = 0.754). Similar findings were shown in 23 track and field athletes (Luebbers and Fry, 2015). Both studies utilised a Smith machine for testing. Luebbers and Fry (2016) compared the test using free weight and Smith machine back squat in 23 track and field athletes and variables measured by a Tendo external dynamometer. Performing the test with the free weight back squat was shown to be valid in trained populations. However, the modalities should not be used interchangeably due the different values obtained for the power variables (Luebbers and Fry, 2016).

Considerations for Testing Power Endurance

Several additional factors should be considered when conducting these tests. Allometric scaling has been studied in relation to muscular endurance (Nuzzo and Mayer, 2013; Markovic and Jaric, 2004). Nuzzo and Mayer (2013) studied the effect of body normalisation with isometric endurance tests. Based on their finding with male firefighters, it was recommended that body mass should be considered when using muscular endurance assessments such as the Biering-Sorenson test or plank test.

Unlike other strength and power assessments, verbal encouragement may have less of an effect on muscular endurance testing (Engel et al., 2019). However, Engel and colleagues (2019) did show improved reliability when verbal instruction was given during muscular endurance performance testing. The actual performance did not differ between the verbal encouragement and no verbal encouragement conditions.

Finally, when measuring power endurance metrics, it is important to establish a true baseline of maximal power to allow for more valid comparisons (Patterson et al., 2019). This can be done by determining this maximal power value on a separate occasion to the power endurance test. The fatigue index should be used with caution due to its poor reliability (Dal Pupo et al., 2014; Cular et al., 2018). The reliability may be improved by controlling the number of jumps performed during the test, introducing a pause between repetitions and ensuring the standardisation of the methods (Patterson et al., 2019; Patterson et al., 2014). It is also critical to carefully monitor technique throughout the test to ensure the repetitions are performed correctly and safely.

Conclusion

Muscular endurance, strength and power are related but should be treated as distinct qualities with assessments. Testing strength and power endurance may be appropriate for certain sports and populations. Sports-specific strength and power tests have been developed based on needs analysis. Researchers and practitioners should use reliable and valid tests, paying attention to the technical aspects of the testing performance. Due to fatigue index measures being less reliable, they should be used with caution by practitioners.

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9

INTERPRETATION OF STRENGTH AND POWER TESTING

Many tests can be used to assess strength and power qualities. Therefore, it is critical to have appropriate analysis tools to effectively interpret the data that are generated from these assessments. As discussed in previous chapters, establishing reliability of strength and power tests being used is an important first step for researchers and practitioners. Unless practitioners can understand the variability in their tests, then interpreting whether a change is meaningful or not becomes problematic. A variety of analysis approaches can be used with strength and power assessments. However, it is important to note that all the analysis in the world cannot overcome poor data collection.

A good source of analysis applications for strength and power assessments is published reports. Historically, not a great deal of information had been published on elite athletes due to concerns with competitive advantage and unwillingness of sporting organisations to share information. However, in recent years increasingly more published reports of testing and training data from elite athletes have become available (Barbosa et al., 2019; Loturco et al., 2019b; Ronnestad et al., 2017; Solli et al., 2017; Baker, 2013; Comfort et al., 2011; Crewther et al., 2011; McGuigan et al., 2009; Sheppard et al., 2008; de Lacey et al., 2014; Loturco et al., 2018, 2017). Case reports of strength and power assessments are also available with clinical populations (Gualano et al., 2010; Idland et al., 2014; Venturelli et al., 2019). This information can be a useful starting point when considering approaches for analysis of strength and power data when working with a specific population.

Analysis Methods for Strength and Power Testing

Interpretation of testing data will be informed by the analysis approach taken. Many methods are available for use by researchers and practitioners. Individualised approaches to the analysis of strength and power testing data should be considered as they can provide rich insights for practitioners (Swinton et al., 2018). One of the challenges is that when testing groups such as athletes and clinical populations, sample sizes may be small (e.g. < 10). Therefore, single-subject or case study analysis methods may be appropriate (Kinugasa et al., 2004; Sands et al., 2019). These approaches can be useful when determining whether real change has occurred in response to a training intervention.

Benchmarking strength qualities have been studied by researchers in order to answer questions such as how much strength or power an athlete requires for their sport. As discussed in Chapters 3 and 5, many studies have been conducted to determine strength and power at various levels of development (Argus et al., 2012; Baker and Newton, 2006; Baker and Newton, 2008; Hoff et al., 2005; Haycraft et al., 2017; Haycraft et al., 2019; Gillen et al., 2019b; Simpson et al., 2019). Understanding what levels of strength and power are required at different levels such as professional, academy and high school can be useful for benchmarking (Argus et al., 2012). Benchmarking involves comparing the results against various levels such as elite world-class performers. Strength is also vital for clinical populations and older adults, so developing benchmarks that can be used to inform analysis approaches to establish levels to optimise health outcomes is of great interest (Cress and Meyer, 2003; Manini et al., 2007). Knowing what levels of strength are required to allow older adults to complete activities of daily living is vital information. Measuring long-term strength and power changes within a programme can provide critical insights for benchmarking (Haugen et al., 2012; Kavanaugh et al., 2018; McGuigan et al., 2009). By comparing the results of the current testing enables determination of where the individual sits relative to their peers.

Establishing normative data for tests allows for comparison by factors such as age, training history, sport and position. However, it is worth noting that normative data will be fluid and change over time. So, there may be limitations inherent to using historical data. Practitioners do need to be aware of the context under which published data were collected when making comparisons with their own data. For example, different equipment used for assessment of power qualities can make comparisons difficult (Chapter 6). Varying technical specifications for the performance of exercises (e.g. depth in squat) could result in differences in 1RM performance (Chapter 3).

Investing time in establishing normative data will influence the choice of the strength or power test. Researchers and practitioners need to be confident that the test being used can be used effectively to inform programming (see Chapter 10). Having "go to" tests can be more useful that regularly switching between different tests. This allows practitioners to establish more effective norms; so while a test might not be perfect, it will allow for more informative comparisons to historical data.

Several different procedures can be used by practitioners to analyse strength and power data, including standardised scores, percentiles and percent change.

Standardised scores are often used with testing data to represent the results. Standard scores such as *z*-scores or *t*-scores can be used. *Z*-scores are commonly used as they represent the results as the number and direction of SD away from the mean (Pettitt, 2010). To calculate the *z*-score, the difference between the athlete's score and mean for the group (or benchmark mean) is divided by the SD for the group (or benchmark SD). Standard 10 (STEN) scores are another option that can be used to convert results to a score out of 10. This may be a more intuitive method for the individuals who are being tested to understand.

Norm-referenced values can be presented as percentiles. Percentiles are often used in increments such as the 80th, 85th or 90th percentile. Practitioners can use these percentiles to see where an individual result for a particular strength or power assessment is placed relative to normative data. Percentage change is another common method for reporting change in testing performance and can be reported alongside raw change in performance. While simplistic methods, these are generally understood by athletes, clients and coaches.

Application of Analysis Methods

Scaling

As discussed in Chapter 2, scaling of strength and power data should be considered by researchers and practitioners (Crewther et al., 2012; Suchomel et al., 2018; Jaric et al., 2005; Jaric, 2002). A general recommendation is that certain assumptions should be met prior to using scaling with the sample being tested, such as normality, homogeneity and linearity (Suchomel et al., 2018). Some researchers have recommended using theoretical allometric parameters (Jaric et al., 2005), whereas others recommend using allometric parameters derived from the population being tested (Nuzzo and Mayer, 2013). Using simple ratio scaling with body mass can be a good starting point for comparing larger groups of individuals. Relative measures of strength and power can be insightful for tasks such as jumping and sprinting as they take into account body mass (Comfort and Pearson, 2014). Bishop and colleagues (2018b) recommended the use of *z*-scores for making comparisons between 1RM in powerlifting to overcome biases that may exist between different lifts and weight classes.

Working with youth can raise challenges in terms of how to express strength and power because of maturation. Studies have suggested that both neuromuscular factors and muscle size are important during growth and development (Tonson et al., 2008; Weir et al., 1999; Gillen et al., 2019a). In a study by Gillen and colleagues (2019a) scaling by height, weight, cross-sectional area and fat free mass did not account for all the differences seen between high-strength and low-strength groups. The authors suggested that measuring both changes in muscle size and neuromuscular factors is needed to fully understand strength changes associated with growth and development.

Various scaling methods for strength and power data have been used with youth athletes (Weir et al., 1999; Morris et al., 2018; Emmonds et al., 2018).

A common approach has been to express strength relative to muscle volume or size (Pitcher et al., 2012; Fukunaga et al., 2014). Maturation should be considered when assessing strength and power in youth (Mirwald et al., 2002). Calculating age at peak height velocity is a method that is commonly used due to its non-invasiveness via anthropometric measures (Mirwald et al., 2002).

Exercise Selection

Strength and power profiling can provide information on exercise selection for strength and conditioning programmes. Performing a needs analysis of the sport and event can help identify tests that may be more specific to the demands of the sport. Several researchers have used this approach in different sports (Pearson et al., 2009; Sheppard et al., 2007). For example, Pearson and colleagues (2009) showed differences in the contribution of maximum strength and power to forward and backward grinding performance in America's Cup sailors.

Load–Velocity Profiling Interpretation

Load–velocity profiling can provide useful insights for strength and conditioning practitioners. Different approaches have been used to measure load profiles in both athletes and non-athletes. For example, Lake et al. (2018a) noted that greater load during CMJ testing significantly increased the time required to produce mean force during the propulsive phase. The authors suggested that by measuring capacity to jump higher in less time with a given load would be useful for monitoring adaptations to ballistic training. Identifying the loads at which individuals can produce the highest levels of variables such as power can provide unique insights for programming (Loturco et al., 2018). However, as discussed in Chapter 6, testing and training at a single load is not recommended and a mixed methods approach to power assessment and development should be used.

Analysis of Force–Time Curves

Force–time curve analysis can provide unique insights into how movement is produced (Cormie et al., 2009; Suchomel and Sole, 2017a; Clark et al., 2008; Suchomel and Sole, 2017b, Wu et al., 2019; McMahon et al., 2017, 2018; Lake and McMahon, 2018). Analysing the different temporal phases of movements, sometimes referred to as waveform analysis or temporal phase analysis, during tasks such as jumping has been performed with athletes (McMahon et al., 2017; McMahon et al., 2018). Additional information from this type of analysis can be an adjunct to strength and power assessment as it allows comparison of how much versus how it is done. For example, analysis has been done to compare force profiles between individuals, with some showing a unimodal (single) or bimodal (two) force peaks during the propulsive and braking phases of jumping (Lake and McMahon, 2018; Kennedy and Drake, 2018; Perez-Castilla et al., 2019). However these methods are not without their limitations (Kipp et al., 2019). Kipp et al. (2019) proposed using statistical parametric mapping to analyse time series data during weightlifting derivatives and jump squats. The method was able to detect differences in the force–time curves of the two exercises. Quantifying various aspects of these curves can be a useful adjunct to power profiling.

Bilateral and Unilateral Assessment

Different approaches have been used to calculate asymmetries (Bishop et al., 2017; Impellizzeri et al., 2007; Bailey et al., 2015; Jordan et al., 2017; Bishop et al., 2016). Given the wide range of methods that can be used, practitioners should think about which approach is the best fit for their purposes as asymmetries will be affected by limb dominance, test type and task demands (Bishop et al., 2016). Practitioners should also consider whether the testing is conducted bilaterally or unilaterally (Bishop et al., 2018a). The method recommended by Bishop et al. (2018a) and Impellizzeri et al. (2007) is preferred for unilateral tests as it considers the stronger versus weaker limb (rather than just dominant versus non-dominant) with the calculation used for the asymmetry index as follows:

$$\text{Asymmetry index} = (\text{stronger limb} - \text{weaker limb})/\text{stronger limb} \times 100$$

Another proposed formula by Bishop et al. (2018a) is:

$$\text{Asymmetry index} = 100/(\text{maximum value}) \times (\text{minimum value}) \times (-1) + 100$$

and then use a function such as the "IF function" in Microsoft Excel to specify the asymmetry direction.

For calculating asymmetries with bilateral testing, methods which take into account differences relative to total performance are preferred (Bishop et al., 2018a; Shorter et al., 2008). The formula proposed by Shorter et al. (2008) can be used:

$$\text{Asymmetry index} = (\text{high} - \text{low})/\text{total} \times 100$$

The analysis methods used for assessing asymmetries also need to be considered (Lake et al., 2018b). For example, Lake and colleagues (2018b) compared mean versus peak methods for calculating force asymmetries during CMJ testing. Due to the differences found it was recommended that the methods not be used interchangeably. The type of test and metrics could also influence the degree of asymmetry (Newton et al., 2006; Bishop et al., 2019a; Heishman et al., 2019; Wells et al., 2019). Figure 9.1 shows an example of differences in the degree of asymmetries for two metrics. For example, differences in asymmetry are seen with jump tests for CMJ, SJ and drop jumps (Wells et al., 2019). All these factors will contribute to the most important part of the testing which is the interpretation of the results. While some suggestions have been made for thresholds of 10–15% asymmetry being a

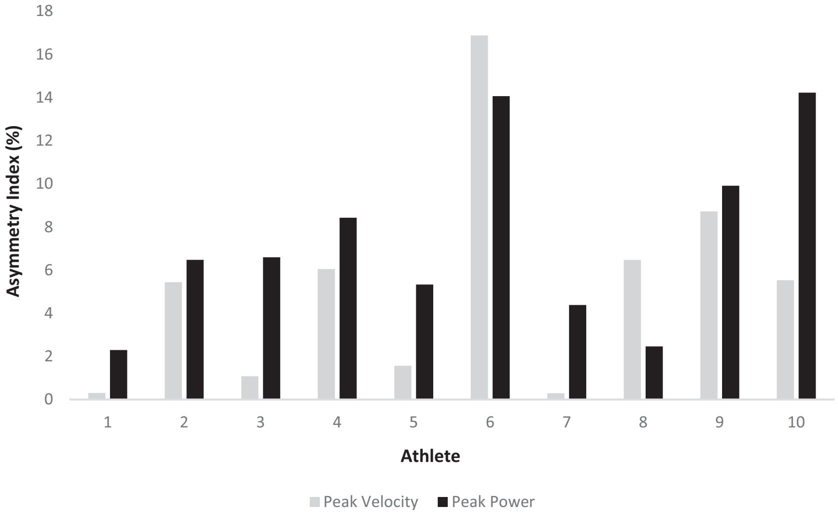

FIGURE 9.1 Squad of athletes showing asymmetries for two different metrics

benchmark for injury prevention (van Dyk et al., 2019; van der Horst et al., 2017; Paterno et al., 2007; Schmitt et al., 2015), it is more likely that the type of test, population and variable are the most critical factors. The relationship between asymmetries and injury risk is not well established. Intralimb variability should also be taken into account with testing (Exell et al., 2012; van Dyk et al., 2019; van Dyk et al., 2018). The degree of asymmetry is not necessarily related to performance in athletes in other tasks such as change of direction and speed (Bishop et al., 2019b; Loturco et al., 2019a; Lockie et al., 2014). The asymmetries have been shown to remain following return to play following injury (Paterno et al., 2007; Jordan et al., 2015; Schmitt et al., 2015; Ithurburn et al., 2018). For example, Schmitt and colleagues (2015) showed that even when returning to play following ACL injury, athletes with the greatest strength deficits had movement asymmetries during landing tasks. Researchers and practitioners are advised to establish the reliability of the metrics and test within the population they are assessing.

Reporting Results

Appropriate presentation of strength and power assessments will assist practitioners with effective interpretation (Buchheit, 2017; Thornton et al., 2019). Many options are available for reporting testing results. Consideration needs to be made for whom the information is being reported to. Reports should be simple, concise and interpretable. Key results should be placed within the context of previous tests and norms for the results. This will assist with showing the value of the testing for the end user. Visualisation of strength and power assessments can be performed using a suite of different tools such as Excel, Google Sheets or R. Visualisation of data can have a large impact on the effectiveness of report. When reporting testing results, consideration should be given to what platform the testing data will appear on. Given that many people now use mobile digital devices for viewing testing reports, this should also be factored in. Having a report that is visually appealing will also contribute to the interpretation of the testing results. Reporting should highlight the most important findings and not overreport to avoid overwhelming the individual. The key metrics (not too many) should be highlighted. Any approach should consider the end user and how to maximise the impact of the testing. Having ongoing discussions with coaches, athletes, clients and/or patients on how they prefer to receive the results of the testing will assist with this process.

Researchers and practitioners should consider which type of visualisation is most appropriate for reporting the results. Alternative approaches to presenting data should be considered (Weissgerber et al., 2015). When presenting team or group-based information, it is useful to visualise the individual data points. Free resources are available for creating graphs to show individual data clearly (Weissgerber et al., 2017). While average data can be interesting, showing individual data is important, particularly when dealing with small numbers of athletes and clients. Certain types of figures lend themselves more effectively for representation of individual data. Representing the individual results can be an excellent way to view outliers.

Turnaround times for testing results should also be considered. The impact of assessment will be maximised only if the data can be acted upon by the coach. This requires that data be collected, analysed and interpreted in a short time frame. The end user needs to be considered when reporting results, and feedback is most useful when it can be used to inform programming and impact change. The advantage of the training-as-testing model, discussed more in Chapter 10, is that it allows for the use of real-time feedback and guiding decisions within the session. Reporting should provide manageable chunks of information that can be easily digested. Front-end information can highlight the key results in relation to previous testing data. Any reporting should also highlight the implications for programming (Chapter 10).

Table 9.1 shows a summary of factors to consider when reporting the results from strength and power assessments.

TABLE 9.1 Checklist for reporting strength and power assessment results

Factors to Consider
• Reliability and validity of the tests • What is a meaningful/worthwhile change in performance? • Comparison to benchmarks and normative data • What is the purpose of the assessments (i.e. what will the information be used for?) • What is the important information to include? • What will be the most effective way to present this information?

Case Studies and Single-Subject Designs

Case studies provide an excellent method for considering aspects of strength and power assessment (Bazyler et al., 2018; Shaw et al., 2019; Loturco et al., 2019b; Kinugasa et al., 2004; Marques et al., 2008; Zourdos et al., 2016; Barbosa et al., 2019). These published reports can provide some fascinating insights into how strength and power assessment fits within an entire programme. Case studies from published research allow practitioners a starting point for considering which assessments have been used for similar sports and populations. A brief summary of some published case studies is outlined below.

Published Case Report of Elite Sprint Swimmer (Barbosa et al., 2019)

The case study by Barbosa and colleagues (2019) showed some fascinating strength and power data for an elite swimmer spanning 2.5 years leading into the 2016 Rio Olympic Games. The strength tests included 1RM for the back squat, bench press and pull up (absolute and relative strength). Peak force, average force, impulse and RFD was also calculated for 10-metre tethered swimming. Published case studies such as this provide practitioners with useful information on long-term training and testing data of elite athletes. Maximal strength assessments of key exercises were able to monitor the athlete's progress over the 2.5-year period leading into the Olympic Games.

Published Case Study Series of Elite Paralympic Powerlifters (Loturco et al., 2019b)

Loturco and colleagues (2019b) reported 1RM bench press and load–velocity relationships in elite Paralympic powerlifters over a range of loads. Strong relationships were reported between the load–velocity relationships and 1RM, particularly at higher loads (> 70% 1RM). Practitioners working with similar populations could potentially use the information for prediction of 1RM and determination of loads for training. Interestingly, the movement velocities were lower than had been previously reported in other athlete groups on the same exercise. This highlights the importance of individualising velocity-based methods.

Published Case Study of Weightlifter Peaking for Competition (Bazyler et al., 2018)

Bazyler et al. (2018) reported a case study of a national level weightlifter peaking for competition. Loaded and unloaded SJ performance were tracked weekly throughout the various training phases leading up to competition. Dynamic mid-thigh pull performance was measured before and after each of the three training phases. Simple power monitoring tests which can be conducted frequently can give practitioners vital information about readiness for both training and competition.

Conclusion

Interpretation of strength and power testing data is critical for practitioners. Several methods can be used to aid with interpretation. Individualised approaches, benchmarking and standardised scores can be useful. Factors such as scaling of strength and power data, along with presentation of results need to be considered. Using data effectively will help with aspects such as exercise selection, load–velocity profiling, analysis of force–time curves and asymmetry interpretation. Case studies and published reports are an excellent starting point for helping to decide which tests to use and how to interpret the information.

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10

STRENGTH AND POWER TESTING TO PROGRAMMING

Strength and conditioning programmes have often taken a one-size-fits-all approach, particularly when working with large groups of athletes. This is also the case with the various exercise guidelines that exist for different populations, particularly for resistance training (Kraschnewski et al., 2014). Many practitioners will use individual approaches to programming which includes ongoing monitoring of responses and adaptations. More individualised approaches have been investigated by researchers with regards to strength and power assessments (Jimenez-Reyes et al., 2016; Jimenez-Reyes et al., 2019). Using these methods can help to inform changes to programmes on a more regular basis (Jimenez-Reyes et al., 2019).

Resistance-training prescription presents challenges for strength and conditioning practitioners. The many training variables that can be manipulated, including exercise selection, number of sets and repetitions, frequency of sessions, lifting tempo, rest periods between sets/exercises/sessions, to name just a few, add to the complexity of the prescription. Therefore, practitioners need to use a range of monitoring tools and assessments to monitor resistance training (Scott et al., 2016).

As outlined in Chapter 3, using percentages of 1RM is a common approach for programming. The method is not without its limitations. Performing 1RM testing is time intensive and can be impractical when testing large numbers of athletes or clients. It can be difficult to perform 1RM testing for all lifts that are part of the programme, so methods of estimation, both for the lift and indirectly for accessory exercises, may need to occur. Strength and power can improve rapidly, so 1RM testing may not be frequent enough for making adjustments with programming. Therefore, using methods that can allow for more regular changes are worth considering.

Long-Term Tracking

Strength and power assessments are particularly useful for longitudinal tracking of individuals and groups (Sheppard et al., 2012; Baker, 2013; McDermott et al., 2012; Kavanaugh et al., 2018; McGuigan et al., 2009; Appleby et al., 2012; Hoffman et al., 2011; Patterson et al., 2019; Lombard et al., 2015; Baker and Newton, 2006). This enables a picture to be built up over time of strength and power characteristics and how training has influenced the different components. Of particular interest in sport is the transition from junior to elite levels (Sheppard et al., 2012). Many cross-sectional studies have characterised the strength and power qualities of different levels of athletes (Argus et al., 2012; Simpson et al., 2019), but longitudinal studies are less common. A study by Sheppard and colleagues (2012) tracked volleyball players transitioning from junior to elite and identified which strength and power characteristics should be prioritised (CMJ height and spike jump). Hoffman et al. (2011) measured strength and power of Division III college football players over 5-year periods. Large changes were seen in 1RM bench press and squat and vertical jump performance. Interestingly, these changes did not necessarily translate into improvements in speed and agility which did not improve to the same extent.

Lombard and colleagues (2015) tracked under 20-year South African rugby players over a 13-year period from 1998–2010. On average, players had greater absolute and relative strength (1RM bench press) and muscular endurance (pull ups) in 2010 compared to 1998. This type of longitudinal data can provide fascinating insights into historical trends, positional differences (e.g. backs versus forwards) and the changing physical demands of sport.

Long-term studies have also been conducted on strength and power characteristics and links to health outcomes (Bassey and Harries, 1993; Frederiksen et al., 2006). Bassey and Harries (1993) measured hand grip strength in 620 older men and women after 4 years and showed age-related declines in strength. Frederiksen and colleagues (2006) also tracked hand grip strength in 8342 participants (age 45–102 years old) over a 4-year period, with age-related declines also demonstrated. This type of research provides important information for practitioners and policy makers about evidence-based guidelines across populations for improving health outcomes via strength and power training.

Testing-Specific Interventions

Reliable and valid tests can be used to assess the effect of specific training interventions. Practitioners require tests that can accurately assess the degree of meaningful change so they can make informed decisions as to whether the intervention has been successful or not. For example, researchers investigated the effect of training to improve repeated jump ability in elite volleyball players (Sheppard et al., 2008). The volleyball-specific repeated effort test was shown to be sensitive for detecting changes in the desired training quality (repeated effort ability). The process followed in these types of investigations (i.e. development and validation of a sports-specific test and utilising the test during a training intervention) is a useful model for practitioners.

Tracking athletes throughout the preseason period or over the course of the training year is commonplace in sport (McLaren et al., 2018; Daniels et al., 2019; Talpey et al., 2019; Ratamess et al., 2013; Kraemer et al., 2004). In particular, in-season training presents unique challenges for strength and conditioning practitioners. Talpey and colleagues (2019) investigated lower body power changes in NCAA Division I lacrosse athletes tested prior to the start and at the end of the season. Decreases were shown in aspects of CMJ and drop jump performance. Interestingly, CMJ jump height was maintained but there was a decrease in relative peak force. Similar findings have been shown in other sports with strength and power qualities decreasing over the course of the season in sports such as wrestling (Ratamess et al., 2013) and football (Kraemer et al., 2004). Practitioners are therefore interested in strategies to maintain strength and power in-season which provides challenges due to regular match play. Strength and power assessment can also track whether it is even possible to improve these qualities during the season (Comfort et al., 2018). Comfort and colleagues (2018) investigated the effects of a 4-week in-season strength training intervention on DSI (ratio of CMJ peak force and isometric) in collegiate athletes. The athletes performed CMJ and IMTP pre and post a 4-week training phase. The study used 24 athletes, and the authors were able to present individual data for the tested variables. The DSI decreased in response to the 4-week in-season strength training (utilising high loads and low repetitions), largely due to increases in IMTP peak force. While previous work has recommended thresholds such as 0.6 or 0.7 (Sheppard et al., 2011), the results do need to be considered within the context of other measures and used on an individual basis.

Using assessments during critical phases of training is valuable for tracking if the appropriate adaptations are occurring. Suarez and colleagues (2019) investigated changes in IMTP force and RFD following specific phases (strength-endurance, strength-power and taper) in weightlifters. Peak force remained stable over the 11-week training period while RFD measures were more responsive to changes in the training. These approaches do rely on using metrics that are both reliable and sensitive to change.

Qualitative and quantitative approaches can be used when tracking strength and power. For example, timelining can be used to provide a visual representation of events (Howells and Lucassen, 2018; Sheridan et al., 2011). Practitioners could graph the results for strength testing and include commentary on important aspects that may have contributed to changes in performance (Figure 10.1). This type of approach can be a useful supplement to quantitative changes in strength and power.

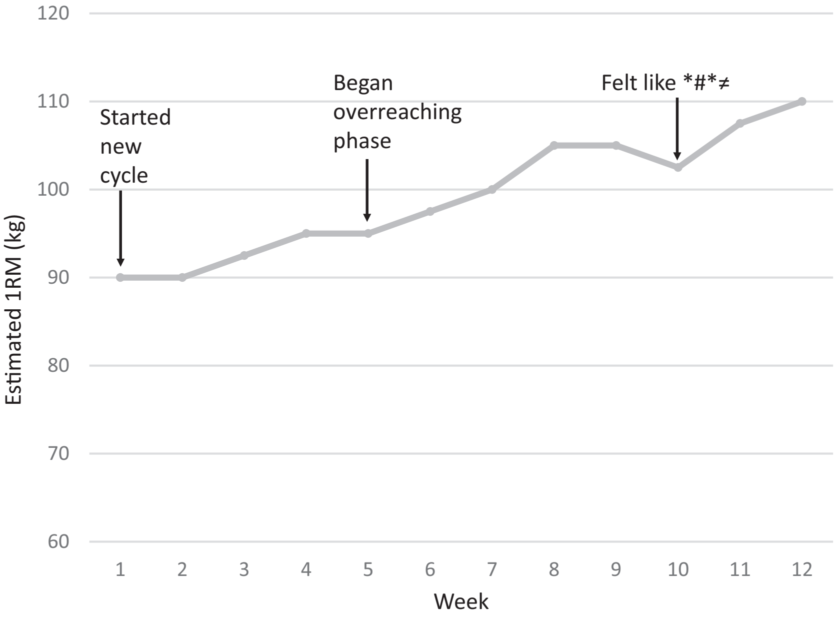

FIGURE 10.1 Timelining of predicted one repetition maximum (1RM) over a 12-week training cycle

Priming is another strategy that can be investigated using strength and power assessments (Kilduff et al., 2013; Harrison et al., 2019; Mason et al., 2017; Russell et al., 2016). Priming refers to performing specific training or exercise sessions in the hours leading up to a competition and has been used anecdotally by coaches for many years. Potentiation effects have been shown up to 48 hours following these resistance priming sessions (Harrison et al., 2019). Practitioners can use specific strength and power assessments to determine the effect of specific sessions. For example, the effects of a lower body priming session could be investigated using vertical jumps. Upper body sessions could be tracked with an assessment such as bench press throws.

Force–Velocity Profiling

Researchers have used force–velocity profiling to individualise training based on whether an individual may be force or velocity deficient (Jimenez-Reyes et al., 2016; Jimenez-Reyes et al., 2019; McMaster et al., 2016). In one study, Jimenez-Reyes et al. (2016) classified individuals following jump force–velocity testing into balanced, velocity deficit and force deficit. Participants were retested following a 9-week training intervention tailored to the characteristics of each group and compared to those undergoing non-optimised training. The results showed greater improvements in jump performance with individualised training. In a follow-up study, Jimenez-Reyes and colleagues (2019) investigated individual adaptations in response to jump training and tapering. Sixty men were allocated to one of four groups based on initial force–velocity profiling that determined if they were force or velocity deficient. The participants were tested every 3 weeks throughout the intervention. The degree of force–velocity of imbalance was also related to the time it took to reach the "optimal" level for the individuals. This ranged from 4–25 weeks in the study, again highlighting the importance of individualisation. The assessments can be conducted regularly (every 1–3 weeks) to allow for regular adjustments to training.

These studies confirm that obtaining regular strength and power testing data allows adjustments to be made to help optimise training to improve jump performance and force–velocity capabilities. Interestingly in the Jimenez-Reyes et al. (2019) study, there were no significant changes in the force–velocity variables following the 3-week tapering period. Tapering is another application of strength and power profiling as it can assist with making informed decisions about when this is needed to achieve peak performance (de Lacey et al., 2014). Several investigations have been conducted that measure these aspects in athletes in relation to tapering (Marrier et al., 2017; de Lacey et al., 2014; Jimenez-Reyes et al., 2019; Pritchard et al., 2019). Strength and power variables appear to have different kinetics during tapering (Marrier et al., 2017; de Lacey et al., 2014). Therefore, individualised approaches to tapering may allow for optimal performance and peaking.

Another study by McMaster and colleagues (2016) investigated upper body force–velocity profiling in 20 semi-professional rugby union athletes. Upper body strength and ballistic profiles were developed for the athletes and comparisons made between positions (backs vs. forwards). Player rankings were also used for different tests (maximum power and maximum velocity) to identify strengths and weaknesses (McMaster et al., 2016). In general, forwards were more force dominant and backs more velocity dominant. However, individual rankings were used to provide detail on deficiencies that required attention. Therefore, these methods can be used to inform training programmes on an individual basis.

Injury Prevention and Rehabilitation

Regular testing of strength and power also has potential to be implemented as part of an injury prevention strategy. Several assessments have been proposed as being useful in injury prevention domain (Wollin et al., 2018; Hickey et al., 2018) with others shown to be less worthwhile (van Dyk et al., 2019). Wollin and colleagues (2018) tracked hip adductor strength, adductor/abductor strength ratio and hip and groin outcome score against thresholds for groin issues in soccer players. Testing was conducted on a monthly basis, and strength-related alerts were identified with at least one of adductor strength decreasing greater than 15% and adductor/abductor ratio less than 0.90. With these alerts, specific interventions (manual therapy and exercise) were implemented to restore these deficits.

Strength and power assessment can play an important role in the rehabilitation process and return to performance. Adequate baseline measures are required to maximise the impact of strength and power assessments for informing return to performance. Several published case studies have used strength assessment to track progress during rehabilitation (Shaw et al., 2019; Joyce and Lewindon, 2015; van Dyk et al., 2019). Studies have tracked the time course of various strength and power variables following injury (van Dyk et al., 2019). Elite female Australian rules footballers still displayed deficits in eccentric knee flexor peak force for several years following anterior cruciate ligament injury and successful rehabilitation (Bourne et al., 2019). It was previously reported that in Australian rules football and soccer players bilateral deficits in peak eccentric knee flexor force still existed several years post injury (Timmins et al., 2016). A study by van Dyk and colleagues (2019) questioned the use of side-to-side differences in isokinetic strength and preinjury levels for assisting decisions about return to performance following hamstring injury in football players.

Other "functional" tests such as the single and triple leg hop for distance have been used to track return to performance following anterior cruciate ligament injury (Logerstedt et al., 2012; Birchmeier et al., 2019). Caution is needed to not simply rely on a single test when assessing rehabilitation (Nagai et al., 2019; Kotsifaki et al., 2019). For example, Nagai et al. (2019) showed differences in asymmetries when using single and triple leg hop, unilateral leg press and isokinetic dynamometry.

A consistent take home message from these investigations is to avoid relying on single measures of strength and power for making decisions regarding return to performance in athletes (van Dyk et al., 2019; Kotsifaki et al., 2019; McAuliffe et al., 2019). It is also critical to use measures that are reliable and valid, in addition to establishing a baseline and determining what constitutes a meaningful change in performance.

Unilateral and Bilateral Assessment to Programming

Using data from unilateral and bilateral assessment can assist practitioners with informing decisions on whether additional unilateral training is required (McGuigan et al., 2013; Bishop et al., 2018). For example, the degree of asymmetry could be used as an indicator if additional single-limb training is needed to help reduce the difference. The ratio of unilateral force and/or power production to bilateral characteristics (also known as the bilateral deficit; Skarabot et al., 2016) is another measure that has been used as a guide to programming. For example, if the testing shows a certain asymmetry and the bilateral deficit indicates the unilateral force production is poor, then more attention is needed for single-leg work.

Different strength and power assessments can be used for measuring asymmetries. For example, Bishop and colleagues (2019b) used a unilateral isometric squat. Peak force was shown to be the most reliable metric, and the findings suggested that targeted interventions could be useful for overcoming imbalances (Bishop et al., 2019b). Providing more information on both unilateral and bilateral force and power capacities can be informative, but practitioners need to avoid making decisions based on single measures or arbitrary thresholds. As discussed in Chapter 9, the degree of asymmetry can vary depending on which assessment is used (Bishop et al., 2019a). These can be used as a guide for programming and help to adjust training programmes.

Clinical Populations

Strength and power assessment can be extremely useful with clinical populations (Barbalho et al., 2018; Ellis et al., 2019). A large body of research has documented strength and power characteristics of different groups of patients (Sahlberg et al., 2005; Beaudart et al., 2019; McGuigan et al., 2001; Galvao et al., 2009; Nygard et al., 2019). Research has also confirmed that strength and power assessments can be performed reliably and safely with older populations (Barbalho et al., 2018). As discussed in Chapter 3, RM testing is very reliable in these populations. However, some evidence has suggested that the degree of worthwhile change (as measured by minimal detectable change) is impacted slightly by training status (Barbalho et al., 2018).

When assessing strength and power in clinical populations it is important to consider "floor" effects with tests being used (Beaudart et al., 2019). For example, using grip strength testing with patients who have upper limb impairment due to rheumatoid arthritis could underestimate muscular strength (Beaudart et al., 2019). When using machines for testing it is also vital to take the ceiling effect into account. For example, some individuals may be able to lift the entire stack depending on the setup and type of machine (Ellis et al., 2019).

Several different assessment methods are available to practitioners for making adjustments to training loads during training programmes when working with these groups. Common approaches include using percentage of 1RM, RM load, RIR and various measures of perceived exertion. One study compared different methods of load progression in 82 older adults (mean age = 72 years) (Buskard et al., 2019). While no differences in the improvements in strength and functional capacity were seen, the RPE method (using the OMNI visual scale) was found to be enjoyable and tolerable in the older adults. The authors suggested that using the RPE method was preferable in this group.

Training as Testing

A recent trend has been to use training sessions for testing and monitoring, rather than requiring as many standalone testing sessions. The development of mobile applications and technologies has provided practitioners with increased options for more easily incorporating testing into training sessions (Peart et al., 2019). The approaches do not necessarily require expensive equipment which makes them within reach of most practitioners.

Use of simple strength and power assessments can be useful for monitoring athletes across a season or particular phase of training (Kipp et al., 2019; Sams et al., 2018). Kipp et al. (2019) used artificial neural networking to effectively model CMJ performance in Division I track and field athletes and volume load across a season. The findings also suggested that the machine-learning approach could provide insights into the magnitude of performance changes due to the variation in volume load. In a study by Sam and colleagues (2018), SJ performance changes were related to changes in training loads (determined from session RPE) over the course of a collegiate soccer season. The studies highlight the usefulness of simple power assessments for tracking athletes and the potential for this data to provide insights into adaptation. Interestingly in the study by Kipp et al. (2019), changes in CMJ performance occurred following weeks with reduced volume loads, highlighting the importance of tapering for helping to drive adaptation in strength and power variables.

The use of velocity-based training is a good example of how training can be used as testing. Due to the relatively robust relationship between velocity and force, it is possible for practitioner to obtain quick and easy estimates of maximum strength. The process of autoregulation has been studied as a training approach using approaches such as barbell velocity, RPE and RIR and allows for daily adjustments to help optimise training and inform decisions for a session (Helms et al., 2018; Banyard et al., 2019; Graham and Cleather, 2019; Zourdos et al., 2016). For example, a training study by Helms et al. (2018) showed that RPE-based loading provided greater improvements in 1RM compared to 1RM percentage–based approaches with periodised programming. Dorrell and colleagues (2019) demonstrated that velocity-based training was more effective than periodised resistance training for improving maximal strength. Velocity-based methods can be sensitive and do not rely on infrequent measures that are used with traditional strength-testing methods. Prescribing training intensity based on measures such as velocity can allow the individual to train according to their "readiness" during the session. The practitioner can make ongoing adjustments during a session based on objective feedback.

The measures (velocity and/or RPE) can be obtained in a warm-up set and subsequent adjustments can be made based on whether the set was performed too quickly/slowly or felt too hard/easy. This would be an ongoing process throughout the session. Decisions need to be made about how to determine specific thresholds for making adjustments. One approach is to determine the thresholds or velocity zones based on previous research and initial testing of the individual/squad/group (Dorrell et al., 2019). For example, velocity "stops" have been used where the set is terminated when the velocity drops 20% below the targeted velocity zone (Dorrell et al., 2019; Pareja-Blanco et al., 2017). It is important that this is done for individual exercises and individuals due to the differences in the force–velocity characteristics. Also, practitioners should avoid being too rigid with these thresholds and not be afraid to be guided by the "art of coaching" and feedback from the athlete or client.

The value of feedback during training sessions and within resistance exercise bouts has been previously demonstrated (Weakley et al., 2019; Nagata et al., 2018; Randell et al., 2011). However, challenges to this method is how practical is it to do this for all exercises in the programme. This will be particularly difficult when dealing with large groups of individuals.

Keeping It Simple, Just Not Too Simple!

While it is important not to overcomplicate strength and power assessment, the same can be said for oversimplification. Strength and power represent a series of related but unique capacities that need consideration in strength and conditioning programmes (Figure 10.2). While one measure can provide insights into the adaptation process following training, in most instances several measures may be required to build up a full individual profile. Research has shown that the mode of strength assessment results in differential changes in response to interventions (Feiereisen et al., 2010; Gentil et al., 2017). For example, Feiereisen et al. (2010) showed large differences in isokinetic strength versus 1RM changes in the assessment of patients with chronic heart failure following resistance training. Gentil and colleagues (2017) had similar findings when comparing isokinetic and 1RM assessment following resistance training in young men. A comprehensive strength and power profile which includes several key measures can help to develop more effective training programmes.

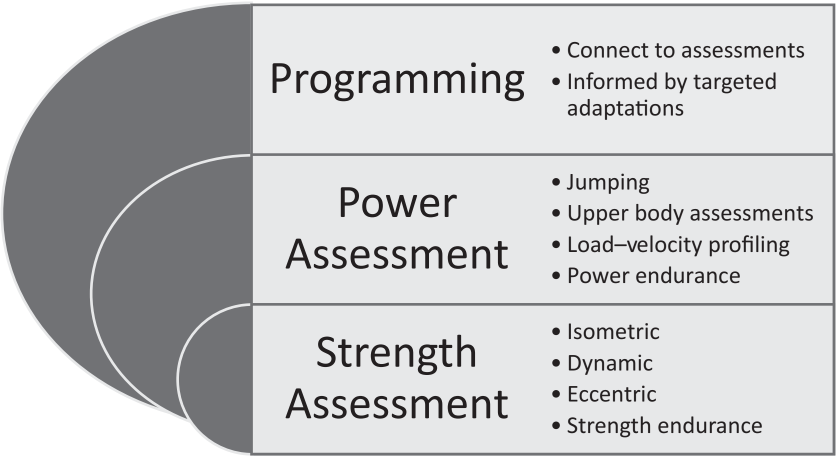

FIGURE 10.2 Interrelationship between strength and power measures and programming

Case Studies

Specific scenarios of how strength and power testing could be implemented are briefly outlined.

Case Study 1

A 19-year-old netballer who plays the centre position. Before the start of the preseason she undergoes initial strength and power profiling. The tests could include an isometric mid-thigh pull, countermovement jump, squat jump, single-leg countermovement jump and drop jump from 45 cm. This would allow for metrics such as DSI, asymmetries and reactive strength to be measured. The results could be benchmarked against previously published data (Simpson et al., 2019; McKenzie et al., 2019; McKeown et al., 2016), although all tests may not have available results to compare against. Standardised scores could be generated to compare the player against her peers or known benchmarks and subsequent strengths and weaknesses identified (Figure 10.3). The

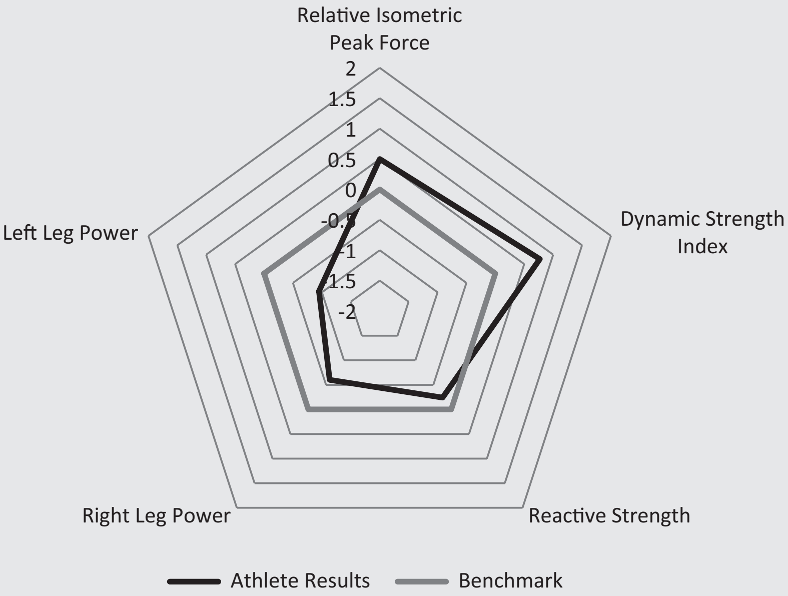

FIGURE 10.3 Radar plot showing athlete z-scores and benchmarks for strength and power profile

profile shows that the athlete has exceeded the benchmarks for relative strength and DSI. However, both reactive strength and single-leg power (particularly left) are below the required standard. This information would form the basis of the training programme design.

Case Study 2

A 35-year-old powerlifter. In addition to estimation of 1RM using RM performance during top sets, velocity-based training and/or autoregulation via RIR could be used as a guide to weekly adjustments in programming. For example, a linear position transducer or accelerometer could be used during warm-up sets for the three key lifts (squat, bench press and deadlift) to assess training readiness and make adjustments to training loads during the session.

Case Study 3

A 64-year-old with peripheral arterial disease and hypertension. Along with the standard tests such as the 6-minute walk, the 10RM calf press can be used to track resistance-training responses. The reliability of the 10RM test has been previously established in this population (McGuigan et al., 2001). The test could be incorporated as part of the patient's training on a weekly basis and used to inform changes in strength, as well as guiding adjustments to the training programme.

Conclusion

The value of strength and power assessments is ultimately determined by their ability to influence programming. Strength and power testing can be applied across several scenarios. Measuring the response to training interventions, injury prevention, tracking rehabilitation, monitoring resistance training, priming and informing training sessions all require valid and reliable strength and power assessments. These methods can be applied with a range of populations. Practitioners should not rely on a single measure of strength or power to assess the responses to a training programme. The assessment and programming should not be viewed as separate, but rather as integrated processes that will work together to result in greater adaptations.

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