

# A Brief Review of Strength and Ballistic Assessment Methodologies in Sport

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**Abstract** An athletic profile should encompass the physiological, biomechanical, anthropometric and performance measures pertinent to the athlete's sport and discipline. The measurement systems and procedures used to create these profiles are constantly evolving and becoming more precise and practical. This is a review of strength and ballistic assessment methodologies used in sport, a critique of current maximum strength [one-repetition maximum (1RM) and isometric strength] and ballistic performance (bench throw and jump capabilities) assessments for the purpose of informing practitioners and evolving current assessment methodologies. The reliability of the various maximum strength and ballistic assessment methodologies were reported in the form of intra-class correlation coefficients (ICC) and coefficient of variation (%CV). Mean percent differences ( $M_{\text{diff}} = \left[ \frac{|X_{\text{method1}} - X_{\text{method2}}|}{(X_{\text{method1}} + X_{\text{method2}})} \right] \times 100$ ) and effect size ( $ES = [X_{\text{method2}} - X_{\text{method1}}] \div SD_{\text{method1}}$ ) calculations were used to assess the magnitude and spread of methodological differences for a given performance measure of the included studies. Studies were grouped and

compared according to their respective performance measure and movement pattern. The various measurement systems (e.g. force plates, position transducers, accelerometers, jump mats, optical motion sensors and jump-and-reach apparatuses) and assessment procedures (i.e. warm-up strategies, loading schemes and rest periods) currently used to assess maximum isometric squat and mid-thigh pull strength (ICC > 0.95; CV < 2.0 %), 1RM bench press, back squat and clean strength (ICC > 0.91; CV < 4.3 %), and ballistic (vertical jump and bench throw) capabilities (ICC > 0.82; CV < 6.5 %) were deemed highly reliable. The measurement systems and assessment procedures employed to assess maximum isometric strength [ $M_{\text{Diff}} = 2\text{--}71$  %; effect size (ES) = 0.13–4.37], 1RM strength ( $M_{\text{Diff}} = 1\text{--}58$  %; ES = 0.01–5.43), vertical jump capabilities ( $M_{\text{Diff}} = 2\text{--}57$  %; ES = 0.02–4.67) and bench throw capabilities ( $M_{\text{Diff}} = 7\text{--}27$  %; ES = 0.49–2.77) varied greatly, producing trivial to very large effects on these respective measures. Recreational to highly trained athletes produced maximum isometric squat and mid-thigh pull forces of 1,000–4,000 N; and 1RM bench press, back squat and power clean values of 80–180 kg, 100–260 kg and 70–140 kg, respectively. Mean and peak power production across the various loads (body mass to 60 % 1RM) were between 300 and 1,500 W during the bench throw and between 1,500 and 9,000 W during the vertical jump. The large variations in maximum strength and power can be attributed to the wide range in physical characteristics between different sports and athletic disciplines, training and chronological age as well as the different measurement systems of the included studies. The reliability and validity outcomes suggest that a number of measurement systems and testing procedures can be implemented to accurately assess maximum strength and ballistic performance in recreational and elite athletes, alike. However, the reader

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needs to be cognisant of the inherent differences between measurement systems, as selection will inevitably affect the outcome measure. The strength and conditioning practitioner should also carefully consider the benefits and limitations of the different measurement systems, testing apparatuses, attachment sites, movement patterns (e.g. direction of movement, contraction type, depth), loading parameters (e.g. no load, single load, absolute load, relative load, incremental loading), warm-up strategies, inter-trial rest periods, dependent variables of interest (i.e. mean, peak and rate dependent variables) and data collection and processing techniques (i.e. sampling frequency, filtering and smoothing options).

## 1 Introduction

A performance profile should encompass the physiological, biomechanical, anthropometric and performance measures pertinent to the athlete's discipline. The measures that comprise an athlete profile in sport may include: aerobic capacity [1–5], anaerobic/lactate threshold [6, 7], repeated sprint ability [8–17], maximum sprint ability (acceleration and maximum speed) [18–36], agility [25, 29, 30, 37–43], maximum strength [18, 44–55], ballistic upper and lower body force, velocity and power production [47, 48, 56–76], muscle architecture [77–80], anthropometry [50, 81–91], functional movement [92–95] and flexibility [96–100]. Combinations of the above variables are often used for talent identification, the creation of national standards and performance tracking for the underlying purpose of determining an athlete's ability to excel in a particular sport and/or athletic discipline [44, 45, 49, 50, 52, 57, 75, 82, 83, 101–118].

To evolve current strength and conditioning practice, physical performance assessments and athlete profiling must be improved and standardized, as this will inevitably allow for direct unbiased comparisons within and between athletes and team/squads of the same sport/athletic discipline. The type of strength, power, speed and conditioning an athlete is exposed to will undoubtedly cause specific neuromuscular and morphological adaptations, which in turn may improve sports specific performance actions, such as tackling, checking, hitting, blocking, fending, sprinting, chasing, evading, kicking, shooting and passing. Strength and conditioning practitioners use a combination of speed, strength, hypertrophy, power and metabolic training phases to elicit sport, positional and individual specific adaptations. [26, 29, 36, 108, 119–133].

The mechanical assessment and analysis of weight-room (i.e. pressing, pulling and squatting) and sport-specific movements (i.e. throwing and jumping) through the use of technology (i.e. force plates, position transducers,

accelerometers and video capture devices) may provide strength and conditioning coaches with the tools required to improve assessment methods to create comprehensive athlete profiles that effectively influence programming. The overall objective of this review is to consolidate current maximum strength and ballistic assessment methodologies in sport and provide practical recommendations for the sport scientist and strength and conditioning coach. Subsequent discussion will provide further insight into the reliability, validity and primary differences between current measurement systems and procedures/methods used to assess ballistic upper and lower body capabilities and maximum strength.

## 2 Methods

### 2.1 Search Strategies

The following electronic databases were searched multiple times between February 1, 2013 and November 1, 2013: MEDLINE, EBSCO Host, Google Scholar, IngentaConnect, Ovid LWW, ProQuest Central, PubMed Central, ScienceDirect Journals, SPORTDiscus and Wiley InterScience between the years of 1980 and 2013. The following keywords were used in various combinations during the electronic searches: 'recreational', 'elite', 'highly trained', 'athlete', 'sport', 'profile', 'physical', 'characteristics', 'maximum', 'strength', 'one-repetition', '1RM', 'isometric', 'dynamic', 'ballistic', 'neuromuscular', 'performance', 'measure', 'capture', 'record', 'quantify', 'assess', 'evaluate', 'track', 'monitor', 'test', 'analyse', 'identify', 'develop', 'reliability', 'validity', 'human movement', 'jump', 'countermovement', 'bench', 'throw', 'squat', 'press', 'deadlift', 'clean', 'mid-thigh pull', 'measurement', 'system', 'technology', 'device', 'method', 'protocol', 'design', 'force plate', 'linear position transducer', 'rotary encoder', 'accelerometer', 'optical sensor', 'jump mat', 'video', 'Vertec', 'output', 'biomechanics', 'kinetics', 'kinematics', 'force', 'power', 'velocity', 'displacement', 'time', 'sampling frequency', 'rate', 'Nyquist theorem', 'cut-off', 'data processing', 'smooth', 'filter'. The searches identified 1175 potentially relevant articles. Following a review of titles and abstracts, the total was cut to 412.

### 2.2 Inclusion and Exclusion Criteria

Original research studies, technical notes, conference abstracts, book sections and online sources focusing on human movement measurement systems, maximum isometric strength, maximum dynamic strength and ballistic upper and lower body assessments were included in the

initial screening phase. The studies were also required to be written in English, all others were excluded. During the final screening, selections were based on the relevance of the identified sources to the assessment of maximum strength and ballistic performance to recreational and elite athletes, alike.

### 2.3 Data Analysis

The reliability of the included studies was reported in the form of intra-class correlation coefficients (ICC) and coefficient of variation (%CV). Mean percent difference ( $M_{\text{diff}} = \left[ \frac{X_{\text{method1}} - X_{\text{method2}}}{X_{\text{method1}} + X_{\text{method2}}} \right] \times 100$ ) and effect size ( $ES = [X_{\text{method2}} - X_{\text{method1}}] \div SD_{\text{method1}}$ ) calculations were used to assess the magnitude and spread of methodological differences for a given dependent variable. Where  $X$  represents the mean of each method (1 or 2) and  $SD$  represents the standard deviation of method one. The studies were grouped and compared according to their respective performance measure and movement pattern. The mean per cent difference calculations do not take into account the variance of the change within and between groups [134], therefore ES calculations were included to account for variance by standardizing the effects allowing for a more accurate comparison within and between measurement systems and movement patterns [134]. The magnitude of an ES varies based on the training status of the athlete, as the adaptive response to training is larger in recreationally versus highly trained athletes [135]. Effect sizes have been classified into the following for recreationally trained: trivial (<0.35), small (0.35–0.80), moderate (0.80–1.50) and large (>1.50); and trivial (<0.25), small (0.25–0.50), moderate (0.50–1.00) and large (>1.00) for highly trained athletes [134].

## 3 Measurement Systems

The technology used to profile athletes is constantly evolving and becoming smaller, lighter and more practical. Equipment has been designed and created to assess the kinematics and kinetics of any and all isometric and dynamic athletic movements (e.g. sprinting, cutting, squatting, jumping, pressing, throwing and pulling) [2, 25, 37, 42, 43, 51, 136–148]. Current measurement systems used to assess these athletic movements include: timing lights [8, 23, 30, 149–153], video devices [154, 155], optical motion sensors [156, 157], general positioning systems (GPS) [2, 8, 158–160], stop watches [30, 41], timing mats [154, 155, 157, 161], position transducers [56, 68, 162–165], force plates [56, 155, 164, 166–172], strain gauges, rotary encoders [68, 173], accelerometers [163,

164, 174–178], magnetometers and gyroscopes [2, 25, 63, 76, 138, 140, 159, 166, 168, 171, 175, 177, 179–185]. These technologies have been validated to measure force, acceleration, displacement, sprint times, change in position and their respective integrated and derived variables.

This information may be used to provide immediate performance feedback, assess the effectiveness of training and track changes over time. Sports scientists have used many of the above measurement systems in controlled laboratory-based settings; and more recently accelerometers have been employed to assess changes in force, velocity and power during the above movements, to assess the effectiveness of training interventions and monitor performance over time [154, 156, 164, 175, 186–189]. A shift to develop smaller, more practical wireless technologies (e.g. wireless accelerometers and GPS) may afford strength and conditioning coaches the opportunity and capability to assess performance changes in the various training environments [190, 191]. However, these commercially available devices (e.g. Myotest<sup>®</sup>, XC2<sup>®</sup>, G-Link-LXRS<sup>®</sup>, AmmSensor<sup>™</sup>) are still relatively untested in terms of measuring kinematics and kinetics during squatting, jumping, pushing and pulling type movements in high-performance environments [163, 164, 175–178, 182]; these technologies therefore require further validation before being used as a monitoring tool in sport.

### 3.1 Sampling, Filtering and Smoothing Techniques

The data collected during these movement patterns are often filtered, smoothed, differentiated and integrated to calculate and predict specific kinematic (displacement, velocity and acceleration) and kinetic (work, impulse, rate of force development and power) variables using built-in and customised software programmes [56, 139, 160, 163, 164, 168, 174, 186, 192–196]. The sampling frequency, filtering and data smoothing techniques applied may also affect the resultant output. A broad range of sampling frequencies (25–1,000 Hz) have been applied to collect and record kinematic and kinetic data across different measurement systems (e.g. video, rotary encoders, position transducers, accelerometers and force plates [56–58, 61, 62, 64, 67, 68, 71, 148, 162, 163, 166–168, 174, 192, 195, 197–204]. Recommendations are based on the Nyquist–Shannon sampling theorem, which states that the critical sampling frequency must be a minimum of two times the highest frequency in the signal of interest to obtain all the information found in the original signal [205, 206]. The movement pattern assessed (e.g. jumping, throwing, pressing and squatting), dependent variables of interest (e.g. mean, peak and rate dependent variables) and measurement system determine the frequency of the signal and in turn the required sampling frequency (Table 1). The

**Table 1** Recommended sampling frequencies for ballistic, dynamic strength and isometric strength testing [165, 195, 205, 242, 244, 300, 326, 329, 335, 337, 347, 375, 403–409]

Movement pattern	Velocity range (m/s)	Rate of force development (kN/s)	Recommended sampling frequency range (Hz)	
Vertical jump	1.50–3.50 <sup>a</sup>	5–15 <sup>b</sup>	350–700 <sup>a</sup>	1,000–1,500 <sup>b</sup>
Bench throw	1.00–2.50 <sup>a</sup>	2–10 <sup>b</sup>	250–500 <sup>a</sup>	200–1,000 <sup>b</sup>
1RM clean	0.50–3.50 <sup>a</sup>	10–25 <sup>b</sup>	350–700 <sup>a</sup>	1,000–2,500 <sup>b</sup>
1RM bench press	0.10–0.70 <sup>a</sup>	5–15 <sup>b</sup>	100–200 <sup>a</sup>	500–1,500 <sup>b</sup>
1RM squat	0.20–1.00 <sup>a</sup>	5–20 <sup>b</sup>	100–200 <sup>a</sup>	500–2,000 <sup>b</sup>
Iso-squat		5–25 <sup>b</sup>	500–2,500 <sup>b</sup>	
Iso-mid-thigh pull		5–25 <sup>b</sup>	500–2,500 <sup>b</sup>	
Iso-bench press		5–15 <sup>b</sup>	500–1,500 <sup>b</sup>	

<sup>a</sup> Recommended sampling frequencies are based on the sampling rates of five to ten times the minimum sampling frequency (which are based on capturing position changes of 5 mm)

<sup>b</sup> Recommended sampling frequencies for rate of force development are based on a sampling frequency to capture force changes of 10 N

required sampling frequency increases with increasing velocity; for example, to capture position changes of 5 mm for movements with velocities between 1.00 and 3.00 m/s, the subsequent measurement system must sample at rates between 20 and 60 Hz [207–210]. Sampling at rates below the critical frequency run the risk of aliasing (i.e. distorting the original signal) and losing vital pieces of the original signal (e.g. peak values) [205]. Regardless of the measurement system employed, it is recommended that the sampling frequency be at least five to ten times the frequency of the signal of interest for human movements to ensure peak values (e.g. peak take-off and impact forces) are not missed [195, 206, 211]. However, when rate dependent variables are included (e.g. rate of force development) sampling frequencies should be much larger (1,000–2,500 Hz). Therefore, the sampling frequencies required to accurately capture maximum dynamic strength (e.g. squat, bench press and clean), maximum isometric strength (e.g. squat, bench press and mid-thigh pull) and ballistic (e.g. bench throws and jumps) movements range from low (100 Hz) to very high (2,500 Hz), respectively.

A number of measurement systems have built-in software programmes that convert the analogue signal to digital, the time-dependent digital data (e.g. displacement, velocity, acceleration and force) is then smoothed and filtered (between 0 and 100 Hz), which is adjusted to reduce noise and signal distortion [195, 203, 204, 206, 212–221]. Displacement, velocity, acceleration and force data are most commonly smoothed using polynomial (e.g. second-

and fourth-order Butterworth filters), splines (e.g. cubic, rectangular and quintic splines), Fourier transforms, moving averages (3–15 data points) and digital filters [67, 166, 195, 203, 204, 206, 217, 218, 220–235]. Human movement occurs at relatively low frequencies (5–30 Hz), therefore low-pass filters (4–10 Hz) are often used to remove the high-frequency noise of the signal [216, 217, 221].

The filtered and smoothed data are then differentiated or integrated depending on the measurement system used to calculate other important variables of interest (e.g. impulse, work and power). As the number of calculations increases, so does the error, for example a position-time data from linear position transducers and rotary encoders must be differentiated and double differentiated to calculate velocity and acceleration, introducing more noise for each successive calculation [230, 236]. For a more detailed description of kinematic and kinetic data collection and analysis methods refer to the following sources [179, 205, 206, 221, 226, 230, 234–238].

#### 4 Ballistic Profiling

Biomechanically, sport is typified by a spectrum of specific force–velocity–power governed actions, such as pushing, pulling, jumping, running, sprinting, cutting, tackling, fending, blocking, kicking and passing [2, 105, 107, 204, 239–242]. Explosive upper and lower body capabilities are generally quantified and assessed via force plates and position transducers [16, 118] technology during explosive pulling, pressing, squatting, jumping and throwing [61, 71, 75, 166, 167, 192, 197, 203, 204, 243–246]. Ballistic movements, such as jumping and throwing allow the athlete to accelerate the body/bar throughout the entire range of motion; producing greater velocity and power outputs than traditional non-ballistic movements [247]. When designing vertical jump and bench throw profiling protocols, the sports scientist and strength and conditioning coach must carefully consider the measurement system (e.g. force plate, position transducer, jump mat, video, accelerometer, optical motion sensors), testing apparatus [bar type (free vs. fixed)], movement pattern (i.e. countermovement, concentric-only, direction of movement, depth), loading parameters [single load, incremental loading, absolute load, relative load (%1RM vs %BM)], warm-up strategy and inter-trial rest periods. A number of different bench throw and vertical jump testing protocols have been implemented to reliably (ICC  $\geq$  0.83; CV  $\leq$  6.4 %) assess vertical displacement (jump and throw height), force, velocity and power across the various absolute and relative loads using the previously mentioned measurement systems [45, 57, 58, 61, 62, 64, 67, 68, 141, 148, 162, 166–168, 181, 187, 192, 195, 197, 199–202, 222, 248–250].

#### 4.1 Ballistic Assessment Strategies

The measurement system used during the ballistic assessment will inevitably affect the resultant kinematics and kinetics. Jump mats and photo-cells predict jump height based on flight time; whereas the reach-and-jump apparatuses (e.g. Vertec) measure jump height directly based on the difference between reach height and the highest obtained jump. Based on jump height and body mass peak power can be predicted using previously developed regression equations. Video capture devices use anatomical landmarks to track movement of the centre-of-mass, which are converted to vertical and horizontal position coordinates via digitisation, jump height is calculated as the rise of the centre-of-mass. Velocity and acceleration are calculated through single and double differentiation of the digitized position-time data; subsequently force (mass  $\times$  acceleration) and power (force  $\times$  velocity) can be determined if the mass of the athlete is known. The force plate predicts jump height from take-off velocity using different methods that include integration of the acceleration-time curve, the impulse-momentum theorem and the work-energy theorem. The force plate calculates power from the ground reaction force and velocity of the centre-of-mass as integrated from the acceleration-time curve; whereas the position transducer calculates power from the system mass (body mass + external load) and velocity of the position transducer attachment point as differentiated from the position-time data. When these two devices are synchronized, power is calculated from the ground reaction force of the force plate and the velocity of position transducer. Based on the above descriptions inter-device differences are expected as the respective kinematics and kinetics are measured and calculated via different parameters.

A number of vertical jump studies have compared the kinematic and kinetic differences between measurement systems (Table 2). [154, 155, 157, 166, 167, 192, 194, 251–253]. Lara et al. [194] reported that vertical jump peak power predictive equations based on jump height and body mass developed by Sayers [253], Harman [252] and Canavan [251] differed from the force plate by 9 % (ES = 0.52), 21 % (ES = 1.19) and 33 % (ES = 1.76), respectively. Other studies also observed trivial to large differences in peak power ( $M_{\text{Diff}} = 2\text{--}22\%$ ; ES = 0.03–1.72) between the force plate, linear position transducer and force plate synched with a linear position transducer during loaded and unloaded squat jumps (Table 2) [166, 202]. Previous researchers using accelerometers found the bar attachment [164, 175] set-up to over-predict ( $\sim 3\text{--}8\%$ ) and the hip attachment [156, 250, 254, 255] to under-predict ( $\sim 2\text{--}6\%$ ) flight time, force and power in comparison to force plate technology. Jump height estimations also varied in direct relation to the

measurement system used [154, 155, 157]. Predicted jump height differences between 2 and 32 % (ES = 0.08–2.27) have been reported between force plates (i.e. calculated from take-off velocity), video, photo-cells, jump mats, accelerometers and jump-and-reach apparatuses (Table 2) [154, 157, 256, 257]. The different devices measure and predict jump height and power based on different parameters, therefore inter-device differences should be expected. Nonetheless, these devices were all deemed highly reliable (ICC > 0.92; CV < 5.6 %) for estimating jump height within and across testing sessions. It must be noted that measurement systems requiring a greater number of steps (e.g. differentiation, integration, multiplication, division, regression analysis) to calculate a specific variable of interest are at a greater risk of increased noise and calculation error [155, 230].

Although less researched inter-device differences were observed during bench throw and explosive bench press assessments [68, 163]. Gomez-Piriz et al. [163] found wireless accelerometry ( $805 \pm 242$  W;  $1.94 \pm 0.50$  m/s) to over-predict explosive bench press peak power and peak velocity by 20 % (ES = 2.77) and 7 % (ES = 1.05) using a 25-kg load, in comparison to a position transducer ( $662 \pm 52$  W;  $1.81 \pm 0.13$  m/s). The within-subject SDs may also suggest that the accelerometer was more variable and less stable than the position transducer. Drinkwater et al. [68] reported a high criterion validity ( $r \geq 0.97$ ) for optical rotary encoders in assessing mean and peak power during a 40-kg Smith machine bench throw in comparison to a digital video camera. A number of studies assessed criterion validity using a Pearson product correlation, while failing to report absolute or mean percentage differences between measurement systems, therefore only partially validating these respective systems [68, 188, 258]. Based on the above studies, the various measurement systems should not be used interchangeably to assess and monitor kinematic and kinetic changes in bench throw and vertical jump performance because of the observed differences (Table 2).

Vertical plane movements using free [56, 148, 166, 181, 195, 202, 204, 222] and fixed bar [45, 57, 61–63, 67, 162, 197, 233] set-ups are most commonly used to assess jump and bench throw capabilities, as they are more easily evaluated using the various measurement systems; and incremental loading can be applied more effectively. Bench throw and vertical jump profiles have been created using incremental load testing [i.e. absolute and relative (%1RM or %BM) loads] [57, 61, 62, 64, 76, 148, 180, 203, 204, 259]. The logistics of these incremental loading schemes should be carefully considered when applied to team sports versus individual athletes, as absolute loading may be more practical (i.e. less time consuming) in team sport settings, where a large number of athletes are tested



**Table 2** A study comparison of ballistic lower and upper body measurement systems

Study	<i>N</i>	Group	Movement pattern	DV	Device	Output
Lower body						
Aragon-Vargas [257]	52	Collegiate M	CMJ	JH	Video	52.0 cm
					FP – TVel	36.1 cm
					FP – Ft	40.2 cm
Cormie et al. [166]	10	Collegiate M	JS	PP	FP	6,261 W
					LPT	6,497 W
					FP + LPT	6,303 W
Cormie et al. [166]	10	Collegiate M	JS 85 %	PP	FP	4,247 W
					LPT	4,403 W
					FP + LPT	4,093 W
Dias et al. [155]	20	Nonathletic M/F	CMJ	JH	Video	37.9 cm
					FP	36.4 cm
					Jump mat	27.6 cm
Garcia-Lopez et al. [157]	89	Students M/F	CMJ	JH	FP	32.7 cm
					Photo cells	31.4 cm
					Jump mat	26.9 cm
Hori et al. [202]	30	Professional AFL M	CMJ 40 kg	PP	FP	3,866 W
					LPT	3,567 W
					FP + LPT	4,427 W
Hori et al. [202]	30	Professional AFL M	CMJ 40 kg	PF	FP	2,151 N
					LPT	2,159 N
Hori et al. [202]	30	Professional AFL M	CMJ 40 kg	PV	FP	1.99 m/s
					LPT	2.23 m/s
Kibele [256]	8	Athletic M/F	CMJ	JH	Video	32.7 cm
					FP – TVel	30.2 cm
					FP – Ft	30.8 cm
Lara et al. [194]	161	Recreational M/F	VJ	PP	FP	3,524 W
					Eqn <sup>Canavan</sup>	2,533 W
					Eqn <sup>Sayers</sup>	3,232 W
					Eqn <sup>Harman</sup>	2,856 W
Nuzzo et al. [154]	40	Recreational M	CMJ	JH	Vertec	47.9 cm
					Jump mat	55.3 cm
					Accel	44.3 cm
Upper body						
Gomez-Piriz et al. [163]	3	Athletic M	EBP	PP	LPT	662 W
					Accel	805 W
Gomez-Piriz et al. [163]	3	Athletic M	EBP	PV	LPT	1.81 m/s
					Accel	1.94 m/s

*Accel* accelerometer, *AFL* Australian Rules Football, *CMJ* countermovement jump, *DV* dependent variable of interest, *EBP* explosive bench press, *Eqn* power predictive equation (W), *F* female, *FP* force plate, *Ft* jump height calculated from flight time, *JH* jump height, *JS* jump squat, *LPT* linear position transducer, *M* male, *N* sample size, *PP* peak concentric power (W), *PV* peak concentric velocity (m/s), *TVel* jump height calculated from take-off velocity, *VJ* vertical jump

within a single session [45, 64, 76, 141, 148, 162, 164, 181, 246, 260, 261]. The use of magnetic braking systems is often advised during heavy load trials as a safety precaution to reduce impact forces on landing [262–264]. Training experience and age should also be taken into consideration when selecting the loading scheme, as more

experienced athletes will most likely have greater tolerance to heavier external loads.

There are two similar, yet distinct bench throw and vertical jump movement patterns used to assess these kinematics and kinematics, the countermovement and concentric-only muscle actions; which are respectively

used to assess the stretch-shortening cycle and concentric-only capabilities of the athlete [75, 148, 265]. The inclusion of both movements in a ballistic performance profile may help determine an athlete's level of stretch-shortening cycle augmentation (i.e. ratio between countermovement and concentric-only performance) [265]. The eccentric displacement (depth) of these ballistic movements will influence the validity, reliability and subsequent kinematic and kinetic outputs, and therefore needs to be carefully considered [141, 266–268].

The depth of bench throw (e.g. bar-to-chest, 90° elbow angle and self-selected depth) and vertical jump (e.g. self-selected, 90° knee angle and parallel) assessments vary between studies [45, 56, 61, 62, 67, 68, 148, 162, 181, 195, 197, 204, 222, 233, 248, 269]. There are inherent benefits and limitations to using self-selected and fixed depths [266, 268]. Two studies investigating the effects of squat jump (SJ) and countermovement jump (CMJ) depth on performance found that as squat depth increased, peak force ( $M_{\text{Diff}} = 16\text{--}57\%$ ;  $ES = 1.41\text{--}3.27$ ) decreased and jump height increased ( $M_{\text{Diff}} = 35\text{--}56\%$ ;  $ES = 2.08\text{--}4.67$ ) [266, 268]. Clark et al. [141] found that the full range (bar-to-chest) bench throw produced greater peak force ( $M_{\text{Diff}} = 27\%$ ;  $ES = 2.38$ ) and throw height ( $M_{\text{Diff}} = 16\%$ ;  $ES = 0.49$ ) in comparison to the half range bench throw using a load of 60 kg. It seems that increasing CMJ and SJ depth may improve jump height and reduce peak force; whereas increasing bench throw depth appears to increase throw height and peak force.

Other ballistic upper and lower body movements, such as horizontal and lateral jumps and throws have also been used to a lesser extent to assess performance in these respective planes [74, 107, 270–277]. Horizontal and lateral jumps and throws may provide the strength and conditioning coach with information regarding the athletes' explosive horizontal and lateral capabilities that could transfer to sport-specific qualities, such as sprint acceleration and change in direction ability [74, 107, 133, 242, 271, 274, 278–282]. Unilateral (e.g. single leg and single arm) ballistic movements have also been used to assess kinematic and kinetic asymmetries for preventative and rehabilitative purposes [242, 274, 279–281, 283–285]. Horizontal, lateral and unilateral ballistic assessments in sport have been under-used in comparison to bilateral vertical jumps, considering the sports-specific application and relevance of these assessments.

Various warm-up and post-activation potentiation strategies (e.g. dynamic stretching, light ballistic loading, plyometric, heavy dynamic loading, isometric contractions, motivation, feedback) have also been implemented to improve ballistic upper and lower body performance (e.g. power, velocity and jump height) [60, 246, 286–300]. Researchers have reported jump height increases of 3–5 cm ( $ES = 0.32\text{--}1.25$ ) and peak power increases of

120–350 W ( $ES = 0.22\text{--}0.77$ ) following heavy load back squats (1–5RM) [9, 255, 288, 299, 301, 302]. According to Kilduff and colleagues [287, 288, 299], it may take 4–12 min to significantly potentiate CMJ and bench throw peak power following a heavy set of back squats and/or bench presses. However, others suggest that bench throw and vertical jump performance (e.g. force and power output) can be effectively potentiated (3–8 %) with as little as 90 s to 3 min rest following moderate load sets (body mass 75 % 1RM) [303–305]. Implementing potentiation exercises as part of the standardized warm-up prior to assessing ballistic upper and lower body capabilities may be a worthwhile strategy. Visual and verbal performance feedback strategies ( $ICC = 0.83\text{--}0.87$ ) have also been shown to improve the reliability of ballistic assessments and performance in comparison to non-feedback strategies ( $ICC = 0.53\text{--}0.74$ ) [306, 307]. Traditional rest periods prescribed between sets range between 2 and 5 min across numerous ballistic upper and lower body profiling studies [45, 57, 61, 62, 67, 68, 148, 162, 166, 181, 192, 197, 203, 204, 233]; implementing longer inter-set rest periods (4–12 min) could also allow for optimal neuromuscular recovery and in turn an increase in ballistic performance. Given this information the reader needs to be cognisant of the inherent benefits and limitations of the various assessment strategies currently available, as they will inevitably affect the resultant kinematic and kinetic outputs.

#### 4.2 Power Production in Sport

Concentric power (peak power and mean power) and jump height are the two most commonly reported ballistic performance variables within sport [22, 33, 49, 58, 61, 64, 71, 73, 75, 181, 204, 248, 286, 308–311]. Peak power can be defined as the maximum instantaneous value achieved during the concentric phase at a given load, whereas mean power is calculated as the area under the concentric portion of a power-time curve using a given load [312]. The load that maximises an athlete's power output is often referred to as the  $P_{\text{max}}$  load; which is often predicted based on a polynomial equation applied to the individual power-load curve; and is expressed as mean or peak power [61, 63, 64, 71, 75, 192, 244, 247, 260, 262, 265, 286, 308, 313–319].  $P_{\text{max}}$  has been reported across a range of bench throw (30–60 % 1RM; 35–70 kg) [45, 61, 63–65, 128, 197, 249, 308, 320] and vertical jump loads (0–60 % 1RM) [56, 57, 64, 148, 166, 167, 192], which is dependent on the measurement system and the group or individual being assessed. Athletes can produce peak power outputs between 450 and 1,500 W during the bench throw using relative loads between 20 and 60 % 1RM (20–80 kg) [45, 64, 65, 197, 309, 321]; and between 3,000 and 9,000 W during vertical jump using loads between body mass (no external load) to

60 % 1RM (0–120 kg) [49, 56, 57, 61, 64, 65, 71, 75, 181, 198, 204, 322]. Mean concentric power outputs between 300 and 800 W during the bench throw using relative loads between 20 and 60 % 1RM (20–80 kg); and between 1,500 and 4,000 W during vertical jumps using loads between body mass to 60 % 1RM have been reported [47, 61–63, 71, 181, 202, 259, 261]. Larger variations in mean and peak power can be attributed to the full spectrum of loads used and the wide range in physical characteristics between various sports and athletic disciplines.

Many of these studies have reported  $P_{\max}$  in their assessments, while failing to report other equally important variables [57, 61, 62, 64, 65, 128, 148, 197]. Kinematic and kinetic variables, such as force and velocity should also be included to provide a greater mechanical understanding of these ballistic movements [67, 180, 195, 222, 246]. The addition of maximum force ( $F_{\max}$ ) and maximum velocity ( $V_{\max}$ ) as assessed during throwing and jumping may provide a more holistic representation of ballistic performance [180, 323].  $F_{\max}$  (velocity = 0 m/s) and  $V_{\max}$  (force = 0 N) encompass the entire force–velocity spectrum, as they are hypothetical maximums produced at extreme ends of the force–velocity curve and could provide valuable prognostic information for athlete profiling and programming, but such a contention requires further validation. This is especially so given the spectrum of force–velocity–power actions in sport.

## 5 Maximum Strength

Maximum strength can be defined as the maximum amount of force (dynamic or isometric) an athlete can produce against an external load during a given movement [324]. Maximum strength is an integral part of most sports, specifically in contact sports, throwing events (e.g. shot put and hammer throw) and weightlifting [18, 33, 46, 83, 100, 106, 140, 242, 325–330]. The following factors need to be considered as they will inevitably affect the maximum strength measure: testing equipment, measurement system, movement pattern, contraction type (i.e. eccentric-concentric, concentric-only and isometric), range of motion (eccentric depth), warm-up strategy, motivation and loading scheme. The different maximum dynamic [57, 162, 174, 248, 326, 331–335] and isometric [242, 326, 336, 337] strength testing methodologies have been deemed highly reliable (ICC > 0.91; CV < 4.5 %) and are subsequently discussed.

### 5.1 Maximum Dynamic Strength Assessment Strategies

The 1RM bench press, back squat and clean are the most common methods of assessing maximum strength in

athletes [18, 22, 27, 45, 70, 72, 73, 144, 197, 202, 240, 244, 308, 326, 335, 338–343]. The required squat depth (i.e. quarter, half, parallel and full) and knee angle (70°–110°) varies between studies, in turn affecting the resultant 1RM [45, 162, 181, 197, 244, 248, 326, 333, 336, 344–347]. The box squat has also been used as replacement and supplementary testing and training exercise and in turn possibly affecting the resultant kinematics and kinetics, but not necessarily maximum strength when performed correctly [45, 65, 267, 305, 347]. Bench press depth was not always identified in the studies, but a bar-to-chest depth is required by the International Powerlifting Federation [348] and a handful of studies [162, 174, 181, 248, 326, 349, 350]. As expected, shallower depths resulted in greater 1RM outputs ( $M_{\text{Diff}} = 49\text{--}58\%$ ; ES = 4.24–5.43) [173, 336]. The use of a fixed lifting apparatus (e.g. Smith machine) versus free-weights also appeared to affect the resultant 1RM squat ( $M_{\text{Diff}} = 2\%$ ; ES = 0.09) and 1RM bench/chest press ( $M_{\text{Diff}} = 8\text{--}13\%$ ; ES = 0.35–0.70) [346, 351]. Submaximal strength tests have also been implemented to accurately assess strength and predict 1RM; mean differences of 0–4 % (ES = 0.00–0.13) have been reported between true 1RM and predicted 1RM bench press and back squat [174, 334, 352, 353]. This information may be useful in determining the athletes 1RM without subjecting them to maximum external loads during testing. The clean (full clean and power clean) instructions were similar between studies: lift the bar explosively in the vertical plane from the floor (first pull) past the knees, followed by an explosive ( $V_{\max}$ ) triple extension of the knees, hips and ankles (second pull), scoop under and catch the bar on the shoulders with the elbows high in a front quarter/full squat position [73, 165, 335, 354].

Previous researchers have implemented many different warm-up strategies, such as the cycle ergometer (5–10 min) [73, 204, 244, 269, 336], dynamic stretching and potentiation exercises to maximize strength [73, 294, 295, 355–360]. Squat, leg press and bench press strength increases of 2–4 % (ES = 0.07–0.21) have been reported following various potentiation strategies (e.g. drop jumps, plyometric push-ups and dynamic warm-ups) [356, 358, 359, 361]. Other studies have also found maximum strength increases of 8–12 % (ES = 0.50–0.64) using various motivational strategies [362–364]. In general, loading patterns progressed from light to heavy (30–100 % 1RM) across three to seven successive sets of two to ten repetitions prior to reaching 1RM; 3–5 min rest was given following each set [45, 57, 73, 162, 165, 174, 181, 197, 248, 326, 333, 357]. Based on the above information, different methods of potentiation strategies may be a beneficial warm-up strategy to further increase upper and lower body 1RM outputs during testing.



## 5.2 Maximum Isometric Strength Assessment Strategies

Maximum isometric strength tests are less accessible and therefore less popular than the 1RM, as a force plate or strain gauge is required to assess these strength qualities (e.g. peak force, mean force and rate of force development) [49, 51, 54, 172, 244, 269, 326, 332, 365]. A number of investigations have reported strong correlations ( $r = 0.76\text{--}0.97$ ) between maximum dynamic strength and isometric force production during similar movement patterns [332, 336, 337, 366]. When converted to system mass (external load + body mass), the peak force produced during isometric squats and mid-thigh pulls was slightly to significantly larger ( $M_{\text{Diff}} = 2\text{--}32\%$ ;  $ES = 0.13\text{--}3.40$ ) than the system mass during the 1RM squat [54, 244, 326, 336, 366]. This information may prove useful for comparing isometric to dynamic strength. The isometric squat ( $90\text{--}140^\circ$ ) and isometric mid-thigh pull ( $120\text{--}145^\circ$ ) knee angles, contraction durations (3–6 s), inter-trial rest intervals (2–5 min) and force plate sampling frequencies (500–1,000 Hz) vary between studies [54, 172, 242, 244, 269, 326, 332, 336, 337, 367–371]. It appears that force capabilities during the isometric squat and leg press increased ( $M_{\text{Diff}} = 1\text{--}70\%$ ;  $ES = 0.05\text{--}1.67$ ) with an increased knee angle beyond  $110^\circ$  ( $110^\circ\text{--}170^\circ$  vs.  $90^\circ\text{--}110^\circ$ ) [336, 365, 369, 370].

The isometric bench press has also been assessed at a number of positions relative to the chest (i.e. 2–50 cm from the chest) and elbow angle ( $90\text{--}135^\circ$ ) using strain gauges and force plates [172, 300, 372–374]. No upper body studies to date have compared or reported differences in isometric force production between the various joint angles; but based on the force-position analysis of the heavy dynamic bench press, it would appear that the greatest amount of force (acceleration) is produced during the initial concentric acceleration phase ( $60\text{--}90^\circ$ ) when the athlete is attempting to overcome the inertia of the external load [375–378].

## 5.3 Maximum Strength in Sport

Maximum strength varies greatly within and between sports and athletic disciplines, depending on anthropometry, morphology, chronological age, training age and experience [46, 48, 66, 112, 308, 325, 350, 353, 379–381]. Maximum isometric forces between 1,000 and 4,000 N have been reported in recreational to highly trained athletes during the isometric back squat and mid-thigh pull movement patterns [49, 51, 54, 244, 269, 326, 332, 336, 337, 366]. The 1RM bench press, back squat and power clean can have a range of 80–180 kg, 100–250 kg and 70–140 kg, respectively [18, 25, 45, 62–64, 72, 73, 107,

166, 197, 204, 244, 260, 309, 321, 326, 335, 339–342, 382, 383]. In competitive sport, heavier athletes typically have superior maximum upper and lower body strength qualities because of an increase in the muscle cross-sectional area [49, 162, 328, 342, 382, 384–388].

The large ranges in maximum dynamic and isometric strength may be a result of the various testing methodologies and large variations in somatotype within and between sports and athletic disciplines. Anthropometric and morphological differences are often off-set by scaling maximum strength to body mass, or by allometrically scaling to a ratio (0.44–0.67) of body mass to allow for an unbiased comparison between athletes [46, 66, 162, 389]. Scaling by a percentage of body mass eliminates body mass bias for the sample of interest.

These isometric and dynamic strength tests can be used to assess and monitor maximum strength adaptations as well as effectively inform weight-room specific programming. However, these weight lifting-based assessments do not necessarily provide a true representation of the required sports specific strength qualities [35, 49, 51, 172, 390]. Sports specific maximum strength tests have also been developed to quantify individual tackling [53, 136, 391], scrumming [51, 53, 55, 142, 390, 392], hitting [393–396], kicking [397, 398] and punching [399–402] capabilities; however, their diagnostic value to strength and conditioning practice remains inconclusive.

## 6 Conclusion

Maximum strength and ballistic qualities vary widely within and across sports owing to the large range in positional and sport-specific requirements and subsequent physical characteristics. When creating a performance profile, the strength and conditioning practitioner needs to carefully consider the benefits and limitations of the various measurement systems, testing apparatuses, measurement system attachment sites, movement patterns, loading parameters, warm-up strategies, rest periods, dependent variables of interest and data collection and processing techniques.

Based on current reliability findings (Table 3), all of the reviewed maximum strength and ballistic assessment methodologies may be implemented to measure their respective measures. The most accurate and reliable methods are not always the most practical, therefore sport-specific and environmental factors should also be considered when selecting a battery of performance tests for assessment and monitoring purposes. Given the methodological differences, comparisons of the same performance measure between research studies were difficult. Therefore, the reader needs to be cognisant of the benefits and limitations of the different

**Table 3** Summary of strength and ballistic lower and upper body assessment methodologies [54, 67, 68, 155, 157, 163, 164, 166–168, 178, 179, 181, 188, 195, 201, 254, 257, 260, 271, 291, 306, 326, 329, 331, 333, 336, 337, 346, 347, 349, 370–372, 403, 405, 410–412]

Movement pattern	Measurement system	Equipment	Depth	Variables	ICC (%CV)
CMJ	LPT	FW	Self-select	PF/MF	0.83–0.99 (<6.5)
SJ	FP	Smith	90° knee	PV/MV	
	Video	LR		PP/MP	
	Accelerometer	BS		JH	
		Goniometer			
CMBT	LPT	FW	Bar-to-chest	PF/MF	0.86–0.99 (<6.5)
COBT	FP	Smith	90° elbow	PV/MV	
	Video	LR		PP/MP	
	Accelerometer	BS		TH	
		Goniometer			
Squat	FW	FW	Full to 1/4	1RM	0.91–0.99 (<4.3)
	FP	Smith	70–140° knee		
		LR			
		Goniometer			
BP	FW	FW	Bar-to-chest	1RM	0.91–0.99 (<4.3)
	FP	Smith	90° elbow		
		LR			
		Goniometer			
Clean	FW	FW	Hang	1RM	0.91–0.99 (<4.3)
	FP	Platform	Power	PF, PV, PP	
	LPT		Full	RFD	
Iso-BP	FP	Barbell	90° elbow	PF	0.95–1.00 (<2.0)
	Strain gauge	LR	5 cm-chest	MF	
		Goniometer		RFD	
Iso-squat	FP	Barbell	90–140° knee	PF	0.95–1.00 (<2.0)
Iso-MTP	Strain gauge	LR		MF	
		Goniometer		RFD	

*BP* bench press, *BS* breaking system, *CMBT* countermovement bench throw, *CMJ* countermovement jump, *COBT* concentric only bench throw, *FP* force plate, *Full to 1/4* eccentric squat depth ranged between a quarter squat to full squat, *FW* free weights: barbell + weight plates, *Iso-BP* isometric bench press, *Iso-squat* isometric back squat, *Iso-MTP* isometric mid-thigh pull, *JH* jump height, *LPT* linear position transducer, *LR* lifting rack, *MF* mean force (N), *MP* mean power (W), *MV* mean velocity (m/s), *NA* not applicable, *PF* peak force (N), *PP* peak power (W), *PV* peak velocity (m/s), *RFD* rate of force development (N·s), *SJ* squat jump, *Smith* Smith machine, *TH* throw height, *5 cm-chest* the distance of the bar from the chest during the isometric bench press ranges from 5 cm to touching the chest, *70–140° knee* relative knee angle (shank angle) ranged between 70 and 140°, *90° elbow* relative elbow angle of 90°

assessment methodologies currently available, as this will inevitably affect the outcome measure. Current physical performance assessments are used to create national standards and develop athlete performance profiles to better inform programming. Athlete performance profiles can be further improved by assessing sport-specific tasks covering the entire force–velocity–power spectrum, such as passing, throwing, shooting, punching, kicking, fending, tackling, hitting and body-checking.

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