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Standardization and methodological considerations for the Isometric Mid-Thigh Pull

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Abstract

The isometric mid-thigh pull (IMTP) is commonly used to assess an athlete's force generation ability. This test is highly reliable and is simple and relatively quick to perform. The data that can be determined from the force-time curves generated by the test have been shown to be closely related to performance capacities in a variety of dynamic athletic tasks. However, within the scientific literature there are inconsistencies in the data collection procedures and methods used for data analysis that may impact the resultant output and the ability to compare and generalize results. Therefore, the primary aim of this review is to identify the differences in IMTP testing procedures and data analysis techniques, while identifying the potential impact this may have on the data collected. The secondary aim is to provide recommendations for the standardization of testing procedures to ensure that future IMTP data is of maximal benefit to practitioners and researchers.

Keywords: Force; Rate of Force Development; Posture; Isometric Strength

Introduction

Maximal strength underpins performance in many athletic tasks (15, 55, 63) and as such, monitoring strength, usually by repetition maximum (RM) testing, is commonly performed by practitioners and researchers. While RM testing is reliable (12, 24, 28), it can be perceived as fatiguing, posing an increased potential for injury risk, and only providing information related to the maximal load lifted. In contrast, isometric testing, such as the isometric mid-thigh pull (IMTP), is potentially safer (18), less fatiguing, and allows for the quantification of peak force (PF), force at a variety of epochs, and can provide several measures of the rate of force development (RFD) (11, 21, 26, 30, 32, 33). The diagnostic ability of these measures may be of importance when considering time constrained tasks within sports, such as jumping, sprinting and change of direction. Importantly, the IMTP has been shown to be highly reliable both within and between sessions, with low variability and low measurement error (8, 11, 18, 24, 26, 27, 32).

Performance in the IMTP has been associated with performance in numerous athletic tasks (7, 18, 30, 33, 40, 41, 45, 46, 49, 59, 64, 66, 67, 69, 72, 73). Specifically, absolute PF has been associated with weightlifting performance (7, 30), 1RM squat and power clean (45-47, 49, 59, 69, 73), 1RM deadlift (18), vertical jump performance (39-41, 53, 60, 64, 67), short sprint and change of direction times (59, 64), sprint cycling performance (60), and throwing performance (72) (Table 1). In contrast, West et al. (71) reported no meaningful relationships between absolute PF and short sprint times or jump height, although they did observe large correlations between relative PF (PF/body weight) and these variables in rugby league players. Similarly, Nuzzo et al. (49) reported only a small relationship between absolute PF and jump height but a large relationship between relative PF and jump height (Table 1). The range of associations between PF and performance in other tasks is summarized in Figure 1. Researchers have also reported relationships between allometrically scaled PF and performance in athletic tasks (60, 72), demonstrating similar correlations to those observed when ratio scaling is used (60).

[Insert table 1 about here]

[Insert figure 1 about here]

Another way to examine the isometric force-time curve is to measure force at specific time epochs (e.g. 50-250 ms). It has been reported that these time specific forces are associated with squat jump (SJ) and countermovement jump (CMJ) height (force at 50-, 90, 250 ms) (41), weightlifting performance (force at 100-, 150-, 200-, 250 ms) (7) and 1RM back squat (90-250 ms) (69). Additionally, allometrically scaled force at 150 ms was reported to be related to mean and maximum club head speed during a golf swing (42), with allometrically scaled force at 50-, 90- and 250 ms also related to jump performance (41) (Table 2). In contrast, however, force at 30-250 ms was not related to 1RM deadlift performance (18).

[Insert table 2 about here]

Equivocal results regarding the relationships between measures of RFD and performance in dynamic athletic tasks have been reported in the scientific literature. When examining how the RFD is quantified two main methods exist within the literature (32). The first method is to quantify the peak RFD (PRFD) that occurs during the IMTP with a predefined moving window, most typically lasting between 2-40 ms (32) (Table 3). When this method is utilized for analyzing the force-time curve conflicting results exist within the scientific literature with some authors reporting significant relationships between the RFD and dynamic performance activities (30, 33, 39, 41), while others report no meaningful relationship with 1RM performance (7, 45-47), or SJ and CMJ performances (40, 49, 67). These difference may be attributable to the moving window, with Maffiuletti et al. (43) cautioning against the use of short windows (e.g. 2 ms) as they may be too sensitive to unsystematic variability and therefore less reliable. The second method for evaluating the RFD is to examine time dependant epochs (32). The use of time dependent epoch has been shown to be an effective method for examining the RFD during the IMTP and relating it to various sports performance tasks. For example, Spiteri et al. (58) report that athletes who produce higher RFD to 90 ms and 100 ms are able to demonstrate faster agility times during a 45 ˚ cutting task. One possible explanation why some RFD measures relate to dynamic performance activities and others do not is the method of calculation and reliability of the method. For example, Haff et al. (32) have shown that the only PRFD measure that is reliable is when a 20 ms moving window is used, supporting previous suggestions by Maffiuletti et al. (43). Conversely, using time dependent epochs such as 0-90 ms, 0-150 ms, 0-200 ms and 0-250 ms to calculate the mean RFD across the specific duration produces much more reliable results and generally have better relationships to dynamic performance measures. Therefore, it is generally recommended that using time specific RFD epochs is warranted when using the IMTP as a performance diagnostic tool (32).

[Insert table 3 about here]

Another method for analysing the force-time curve derived from an IMTP is to examine the isometric impulse (67, 68). For example, impulse values across different epochs (0-100, 0-200 and 0-300 ms) have been associated with 5- and 20 m sprint times as well as 505 change of direction times (64), peak force and power during the SJ and CMJ (68) (Table 4). While determining the isometric impulse of various epochs within the force-time curve achieved during the IMTP yields useful information much more research is needed to understand how best to utilise this measurement in a sports performance monitoring program.

[Insert table 4 about here]

The PF achieved during the IMTP has also been used to monitor adaptations to training (5, 36, 50, 51, 57, 70, 74), with some authors also including RFD (36, 51, 52, 74). PF and peak RFD have also been used in an attempt to identify levels of fatigue or recovery (4, 29, 35, 44). More recently researchers have started to investigate the potential of the IMTP to investigate between-limb asymmetries, using dual force platforms (1-3) and a unilateral stance IMTP (25, 65). Additionally, the PF during the IMTP has been divided by the PF during a SJ or CMJ, to calculate the dynamic strength index (DSI; ratio of PF during the CMJ or SJ and IMTP PF), in attempt to identify if an athlete needs to focus more on maximal force production or rapid dynamic force production (14, 52, 54, 56, 66).

Variation in Testing and Data Analysis Procedures

Unfortunately, there is substantial variation across testing protocols reported within the scientific literature, including differences in knee and hip joint angles (120-150° and 124-175°, respectively), sampling frequency (500-2000 Hz), pull onset identification thresholds including absolute (20-75 N) and relative (2.5-10% body weight) threshold values, and smoothing and filtering approaches, with some authors not stating hip angles, thresholds or filtering procedures (Table 5). In addition, if practitioners or researchers are intending to use published values for comparison they should be mindful that some data is presented as net force (gross force – body weight) while others report gross measures, along with ratio and allometric scaling used in some studies. These two latter approaches may impact the results less, as allometric scaling uses an exponent related to body mass (13) although allometric scaling will reduce the resultant values compared to ratio scaling, with greater variation introduced depending on the exponent used (Table 5).

[Insert table 5 about here]

Numerous authors have suggested that the posture adopted during the IMTP should replicate the start of the second pull phase of the clean, (30, 31, 33, 60); however, only two studies have actually assessed the participants knee joint angles during the clean and then adopted these angles during the IMTP (30, 31). This is most likely due to time and practicality of assessing specific joint angles during the clean prior to performing the IMTP, especially when assessing large squads of athletes. Interestingly, hip joint angles were not reported within these two studies (30, 31).

Due to the variety of knee and hip joint angles reported within the literature, Comfort et al. (11) investigated a range of knee (120°, 130°, 140°, 150°) and hip (125°, 145°) joint angles, along with self-selected posture (knee 133±3°, hip 138±4°) based on the athletes preferred position to start the second pull of a clean, which is what the posture adopted during the IMTP was originally based on (33). The results of the study indicated that there were no significant or meaningful differences in PF, PRFD or impulse between postures, although the preferred (self-selected) posture demonstrated the highest reliability and the lowest measurement error. In contrast, Beckham et al. (6) found that powerlifters produced greater PF during an isometric testing with a vertical torso compared to a deadlift-specific body position at the same bar height, described as being a "relatively straight legged position and somewhat bent over the bar". The authors suggested that the upright position may have provided a mechanical advantage and a posture more optimal for force production against the bar. In another study, Beckham et al. (8) compared the effects of different hip joint angles (125° vs. 145°), while standardizing the knee joint angle (125°) reporting meaningful and significantly higher PF and force at different epochs (50, 90, 200, 250 ms) in the more upright (145°) position, especially in subjects with greater experience in performing weightlifting exercises and their derivatives, in contrast to Comfort et al. (11). Interestingly, Beckham et al. (8) reported small changes in joint angles throughout the execution of the test and based on these observations recommend that in the future researchers and practitioners should adopt standardized knee and hip angles of 120-135° and 140-150°, respectively.

More recently, Dos'Santos et al. (26) compared hip joint angles of 145˚ and 175˚ with a standardized knee joint angle of 145˚, finding greater time specific force values and RFD at predetermined epochs, with a 145˚ hip angle (Table 5). The hip angle of 175˚ previously reported by Kraska et al. (41) and replicated by Beckham et al. (6) actually refer to trunk angle relative to vertical, to ensure an upright trunk (forward lean of 5˚ from vertical), exhibiting an upright trunk as previously described (30, 31, 33, 60) rather than a 175˚ hip angle as used by Dos'Santos et al. (26). The authors of a recent meta-analysis also highlight the fact the practitioners should carefully consider the specific protocol, including joint angles, to ensure repeatability of the measures (27).

While adopting standardized knee and hip angles during the IMTP may seem logical, this practice may place athletes in a sub-optimal pulling position, due to the range of angles reported across individuals for the second pull phase of the clean (30, 31). Therefore, it is best to consider the individual athletes' appropriate second pull position and then quantify the knee and hip angles. This practice allows for the individual athlete's anthropometrics to be considered and allows them to assume an optimal pulling position, in line with the range of joint angles recommended by Beckham et al. (8). Once the pulling position is established then it is recommended that practitioners and researchers ensure that the individual starting postures are replicated between trials and testing sessions. Joint angles should be assessed prior to the commencement of the pull due to slight changes in joint angles during the pull (8).

Haff et al. (32) suggest using minimal pre-tension prior to initiation of the pull, as this is likely to impact both time specified force and RFD, with Dos'Santos et al. (26) recently reporting that the 175˚ hip angle results in significantly higher 'body weight' due to increased pre-tension, compared to a 145˚ hip angle, which may have contributed to in the differences in time specific force values and RFD that were reported. Similarly, Maffiuletti et al. (43) suggested that pre-tension is undesirable when assessing isometric RFD, albeit with a focus on single joint assessment; it would, therefore, be advantageous to visually inspect the force-time data pre and post isometric pull, to ensure that there are no differences in force, which should represent body weight.

Interestingly, numerous authors state that they have adopted the postures previously reported by other researchers, but in fact report different angles to those stated in the studies that they cite, or cite multiple researchers who reported different postures (Table 5). These differing postures are most likely related to individual athlete anthropometric profiles. It is therefore important that researchers carefully report and justify their choice of joint angles, but more importantly, standardize these between trials and testing sessions.

Other researchers have used strain gauge based equipment, with the handle attached via a chain (16, 17, 37, 38, 48) with a range of sampling frequencies (100-133 Hz (17, 37, 38)) and joint angles (knee 120-130˚ (17), 142±4˚(38), 143±7˚ (37), 160˚ (48); hip 139±4˚ (38), 144±5˚ (37)). However, findings of two research groups that compared strain gauge systems to a force platform demonstrated that the strain gauge significantly underestimated PF, by ~8% (38) to ~10% (20). Additionally, James et al. (38) found that measures of RFD did not meet acceptable standards of reliability. While such systems can measure PF, which can be ratio or allometrically scaled, there does not seem to be an effective way to accurately measure or calculate RFD, and are therefore not recommended if practitioners have access to a force platform.

Recommendations for Correct IMTP Assessment

Due to the noticeable variations in assessment procedures, including posture, sampling frequency, and methods of calculating specific variables (namely use of different sampling frequencies, onset thresholds, and the method for the calculation of RFD), we suggest appropriate standardization of all testing procedures for the IMTP. Such standardization should permit more meaningful comparisons of individual performances between testing sessions, comparisons between athletes and more effective comparisons between published studies. Standardization should also include the verbal cues as attentional focus has been shown to affect force production, with an external focus of 'push as hard and fast as possible' resulting in greater PF compared to an internal focus (34).

Recommended Testing Procedures

Prior to initiation of IMTP testing, the bar height necessary to obtain the correct body position should be determined. This should be an iterative process in which the athlete starts with a bar height that allows the athlete to assume a body position that replicates the start of the second pull position during the clean. The bar height should then be adjusted up or down to allow the athlete to obtain the optimal knee (125-145°) and hip (140-150°) angles (6, 8, 26). The body position should be very similar to the second pull of the clean and the clean grip mid-thigh pull exercise (19): upright torso, slight flexion in the knee resulting in some dorsiflexion, shoulder girdle retracted and depressed, shoulders above or slightly behind the vertical plane of the bar, feet roughly centered under the bar approximately hip width apart, knees underneath and in front of the bar, and thighs in contact with the bar (close to the inguinal crease dependent on limb lengths) (Figure 2). When making joint measurements, the athlete should ensure that no tension is applied to the bar but that all "slack" (e.g. elbow flexion, shoulder girdle elevation/protraction) is removed from the body, as this would result in a change in joint angles during the maximal effort which is undesirable (8).

[Insert figure 2 about here]

While the use of a "self-selected" body position is likely beneficial to efficiency of testing, it is not recommended without ensuring that the hip and knee joint angles fall within the ranges recommended above, due to the influence of body positioning on force generation (6, 8, 26). The bar height used and joint angles obtained should be recorded so that repeated measurements can be standardized and therefore replicate the individuals' body position between session, ensuring that differing results in subsequent testing are not the result of changed body position (8, 26). It is also considered best practice to measure the individuals grip width and foot position and standardize these for individuals across sessions (unless working with youth athletes where changes in stature as a result of maturation may require increased stance and grip width) as each can affect body positioning relative to the bar (19). After the bar height and posture have been established, a short familiarization session of submaximal trials is recommended approximately 48 hours prior to testing (e.g. 3 x 3 second trials, each of 50-, 75- and 90% of perceived maximum effort). While a consensus on the optimal amount of familiarization has not yet been reached, nearly all IMTP studies use some familiarization.

Athletes should complete some manner of standard generalized warm-up (62). While there is variability in the generalized warm-up chosen among studies, most studies use a warm-up that incorporates clean derivatives, such as the dynamic mid-thigh pull, and should thus be a component of the standard warm-up (7, 21, 24, 32, 33). Submaximal trials of the IMTP are also recommended prior to maximal effort trials (e.g. 3 seconds each of: 50% maximal effort, 75% maximal effort, 90% maximal effort, separated by 60 seconds rest). During this time, the athlete should be secured to the bar using lifting straps and athletic tape to ensure that grip strength is not a limiting factor (Figure 3) (30, 33).

[Insert figure 3 about here]

For each of the maximal effort trials, standardized instructions should be given to the athlete of some iteration of "push your feet into the ground as fast and as hard as possible" to ensure that both maximal RFD and PF are obtained (10, 34). It is essential that athletes understand that the focus is to drive the feet directly into the force platform and not attempt to pull the bar with the arms, or rise up on to their toes. The athlete should get into the correct body position for the IMTP, using just enough pre-tension to achieve the correct body position and remove "slack" from the body, but without any more pre-tension than is necessary to get the "quiet standing" necessary for a stable force baseline (43). This can be verified by monitoring the athlete's body positioning and ensuring the force trace created by the athlete is both similar to body mass and steady, with trials where a change in force >50 N occurs during this period rejected (21). This should be explained to the athletes and they should be encouraged to stay as still as possible during this period to accurately determine body weight and onset threshold. A countdown of "*3, 2, 1, PULL!*" gives the athlete sufficient warning to be ready to give a maximum effort and provides at least one second of quiet standing to enable the identification of the onset of the pull (Figure 5a). Strong verbal encouragement from researchers and teammates ensures that the athlete gives a maximum effort (9). A minimum of two trials should be collected, provided that each of those trials have no errors by the athlete (e.g. countermovement, excessive pre-tension, leaning on the bar prior to the pull (Figure 4). With increasing PF, additional trials should be performed, until the PF values of the trials are separated by <250 N (30, 33). It is noted, however, that a percentage of peak force may be advantageous as an absolute value will affect stronger and weaker athletes differently, although the exact effect of this has not been investigated.

[Insert figure 4 about here]

Visual inspection of the force-time curves during testing can easily be used to determine if the trials are acceptable, or if additional trials should be performed. In addition to the trials being within 250 N between attempts, trials should be repeated if there is not a stable weighing period (clear fluctuation in the force-time data) or a clear countermovement prior to the initiation of the pull (Figure 5c), as this will interfere with accurate identification of the initiation of the pull (19), or if the PF occurs at the end of the trial (Figure 5b). It is also important to check that the force during the initial period of quiet standing (in the ready position, strapped to the bar, immediately prior to commencing the pull) represents body weight, and therefore no prior tension has been applied (Figure 5a) as this will interfere with pull onset identification (19).

[Insert figure 5 about here]

Recommended Data Analysis and Reporting

Collection of IMTP force-time data can be compiled accurately with a sampling frequency as low as 500 Hz , but if higher sampling frequencies can be used then they are preferred as they may increase the accuracy of time dependent measures (21). Specifically, the utilization of frequencies ≥1000 Hz are recommended especially if early force-time variables are of interest (e.g. force at 50 or 100 ms) (21). There are not enough data for a consensus regarding optimal filtering and/or smoothing methods for the IMTP (23); although unfiltered data has been suggested as optimal for analysis of countermovement jump performance (61) and where possible, unfiltered data for isometric testing (23, 43). It is therefore suggested that unfiltered and non-smoothed data is used for subsequent analysis (23), as most of the RFD and impulse characteristics are dependent upon an accurate determination of the start of the pull (21), although data from portable force platforms may exhibit greater 'noise' and warrant smoothing. Accurate identification of the start of the inflection point is often achieved using automated methods - we recommend using 5 standard deviations of body weight during an initial one second weighing period prior to the (usually one second) of quiet standing (in the ready position, strapped to the bar, immediately prior to commencing the pull) as the threshold for determining the onset of the pull (21), although this may vary with technical idiosyncrasies of different force platforms (e.g. noise magnitude). Trials that do not have a stable baseline force trace during the weighing period (change in force >50 N) should be rejected and subsequently another trial should be performed (21, 43) (Figure 5). To facilitate this stable period, it is essential to enforce and practice this during the warm-up / familiarization trials.

It is recommended that time-specific RFD epochs (50-, 100-, 150-, 200- and 250 ms commonly reported) should be used when using the IMTP as a sport performance diagnostic tool as these are not only reliable (32), but can be selected specific to the durations relevant to the specific sporting tasks, such as ground contact time during acceleration or peak running speeds. In contrast, maximal strength capabilities can be inferred from PF (Table 1).

When reporting results from IMTP testing, it is important that the hip and knee angles used by each athlete, to establish the bar height, be reported (8, 26). Such standardization of posture between trials and testing sessions ensures that data is comparable between sessions, groups of athletes and studies (8, 26). While there is no consensus as to the superiority of either net or gross force values for the IMTP, it is important that researchers report whether body weight was or was not included in the force and impulse values reported (7). Other methodological considerations, such as the method for identifying the onset of the pull (and threshold) (21), methods used for smoothing/filtering force platform data (23), sampling frequency and other aspects of analysis (22), such as the exponent used for allometric scaling, should be reported, as each are important for accurately interpreting results from the study.

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Figure and Table Legends:

Figure 1: Relationships between isometric mid-thigh pull peak force and performance in other tasks

Figure 2: Correct posture for the isometric mid-thigh pull, illustrating an upright trunk, replicating the start position of the second pull of the clean

Figure 3: Standardized warm-up procedure

Figure 4: Standardized isometric mid-thigh pull testing procedure

Figure 5: Examples of acceptable and unacceptable isometric mid-thigh pull force-time traces

Table 1: Relationships between peak force and performance in other activities

Table 2: Relationships between time specific force and performance in other activities

Table 3: Relationships between rate of force development and performance in other activities

Table 4: Relationships between time specific impulse and performance in other activities

Table 5: Reported testing and data analysis procedures

Table 1: Relationships between peak force and performance in other activities

Author(s)	Subjects	1RM	Sprint	Jump	Change of Direction	Other
Haff et al. (39)	8 trained (>2 years) men 1RM PC = 1•21 kg.kg^{-1}			SJ PF: r = 0.76		Force during dynamic MTP 90% 1RM: r = 0.77 100% 1RM: r = 0.80
Stone et al. 60	30 competitive sprint cyclists			CMJ height: r = 0.59 CMJ PP: r = 0.79 SJ height: r = 0.51 SJ PP: r = 0.78		Absolute PF & Sprint cycling performances: r = 0.49-0.55 Relative PF & Sprint cycling performances: r = 0.45-0.60 *AS* PF & Sprint cycling performances: r = 0.45-0.58
Haff et al. (30)	6 elite women weightlifters	Snatch: r = 0.93		CMJ PP: r = 0.88 SJ PP: r = 0.92		
Kawamori et al. (39)	8 male collegiate weightlifters 1RM PC = 1.39 kg•kg^{-1}			CMJ PF: r = 0.87 CMJ PRFD: r = 0.85 CMJ PP: r = 0.95 CMJ height: r = 0.82 SJ height: r = 0.87		Force during dynamic MTP 90% 1RM: r = 0.82
McGuigan et al. (47)	8 division III collegiate wrestlers	PC: r = 0.97 Squat: r = 0.96 BP: r = 0.73				
McGuigan & Winchester (45)	22 college football players 1RM PC = 1.11 kg•kg^{-1} 1RM Squat = 1.75 kg•kg^{-1}	PC, Squat, BP: r = 0.61-0.72*				
Nuzzo et al. (49)	12 division I collegiate athletes 1RM PC = 1.28 kg•kg^{-1} 1RM Squat = 1.91 kg•kg^{-1}	PC: r = 0.74		CMJ PP: r = 0.75 Relative PF & CMJ height: r = 0.59		
Kraska et al. (41)	41 female and 22 male collegiate athletes			SJ: r = 0.40 SJ20: r = 0.55 CMJ: r = 0.36 CMJ20: r = 0.55 *AS* PF:		

				SJ: r = 0.47 SJ20: r = 0.52 CMJ: r = 0.41 CMJ20: r = 0.52		
Whittington et al. (72)	7 NCAA Division I track and field athletes					Ball throw distance PF: r = 0.89 *AS* PF: r = 0.91
McGuigan et al. (46)	26 recreationally trained men 1RM Squat = 1.30 kg•kg^{-1}	Squat: r = 0.97 BP: r = 0.99		CMJ height: r = 0.72		
Khamoui et al. (40)	19 recreationally trained men			Relative PF & CMJ height: r = 0.61		Relative PF & high pull PV: r = -0.60
West et al. (71)	39 professional rugby league players		*Relative PF* & 10 m sprint time: r = 0.37	Relative PF & CMJ height: r = 0.45		
Spiteri et al. (59)	12 competitive female basketball players	IMTP relative PF, back squat: r = 0.81			T-Test: r = -0.85 505 COD = -0.79	
Winchester et al. (73)	26 recreationally trained men 1RM Squat = 1.30 kg•kg^{-1}	Squat: r = 0.97 BP: r = 0.99		CMJ height: r = 0.72		
Secomb et al. (53)	15 elite surfers			CMJ height: r = 0.65 SJ height: r = 0.58		
Beckham et al. (7)	12 collegiate-national level weightlifters	Snatch: r = 0.83 Clean & Jerk: r = 0.84 Total: r = 0.84				
Thomas et al. (64)	14 collegiate team sport athletes		5 m: r = -0.57 20 m: r = -0.69		505mod: r = -0.57	
Thomas et al. (67)	22 collegiate team sport athletes			CMJ PF: r = 0.45		
Wang et al. (69)	15 collegiate rugby players	Squat: r = 0.866				

PC = Power Clean; BP = Bench Press; SJ = Squat Jump; CMJ = Countermovement Jump; 505mod = Modified 505 change of direction
PF = Peak Force; PP = Peak Power: PV = Peak Velocity; PRFD = Peak Rate of Force Development; *AS* = Allometrically Scaled
*Individual correlations not reported

Table 2: Relationships between time specific force and performance in other activities

Author(s)	Subjects	1RM	Sprint	Jump	Other
Kraska et al. (41)	41 female and 22 male collegiate athletes			PF50 SJ: r = 0.33 SJ20: r = 0.52 CMJ: r = 0.27 CMJ20: r = 0.50 *AS* PF50: SJ: r = 0.33 SJ20: r = 0.48 CMJ20: r = 0.45 PF90 SJ20: r = 0.37 CMJ20: r = 0.33 *AS* PF90: CMJ20: r = 0.48 PF250 SJ: r = 0.39 SJ20: r = 0.56 CMJ: r = 0.34 CMJ20: r = 0.54 *AS* PF250 SJ: r = 0.42 SJ20: r = 0.51 CMJ: r = 0.34 CMJ20: r = 0.48	
Beckham et al. (7)	12 collegiate-national level weightlifters	F100 Snatch: r = 0.65 Clean & Jerk: r = 0.64 Combined Total: r = 0.65 F150 Snatch: r =0.64 Clean & Jerk: r = 0.61 Combined Total: r = 0.62 F200 Snatch: r = 0.73 Clean & Jerk: r = 0.71			

		Combined Total: r = 0.72 F250 Snatch: r = 0.80 Clean & Jerk: r = 0.80 Combined Total: r = 0.80			
West et al. (71)	39 professional rugby league players		F100 & 10 m: r = -0.66 Relative F100 & 10 m: r = -0.68	F100 & CMJ PP: r = 0.55 Relative F100 & CMJ PP: r = 0.38 Relative F100 & CMJ height: r = 0.43	
Wang et al. (69)	15 collegiate rugby players	Squat F90: r = 0.76 F100: r = 0.78 F150: r = 0.78 F200: r = 0.77 F250: r = 0.82			
Leary et al. (42)	12 recreational golfers				*Golf Club Head Speed* *AS*F150 & Mean Club Head Speed: r = 0.46 *AS*F150 & Max' Club Head Speed: r = 0.47
F90 = Force at 90 ms; F100 = Force at 100 ms; F150 = Force at 150 ms; F200 = Force at 200 ms; F250 = Force at 250 ms *AS* = Allometrically Scaled; SJ20 = Squat Jump with 20 kg; CMJ20 = Countermovement Jump with 20 kg					

Table 3: Relationships between RFD and performance in other activities

Author(s)	Subjects	1RM	Sprint	Jump	Change of Direction	Other
Haff et al. (33)	8 trained (>2 years) men 1RM PC = 1.21 $kg\bullet kg^{-1}$			PRFD SJ Power: r = 0.76 SJ Height: r = 0.82		RFD during dynamic MTP 80% 1RM: r = 0.84 90% 1RM: r = 0.88 100% 1RM: r = 0.84
Haff et al. (30)	6 elite women weightlifters	PRFD Snatch: r = 0.79 Combined Total: r = 0.80		PRFD CMJ PP: r = 0.81 SJ PP: r = 0.84		
McGuigan et al. (47)	8 division III collegiate wrestlers					PRFD & Coaching Ranking: r = 0.62
Kawamori et al. (39)	8 male collegiate weightlifters 1RM PC = 1.39 $kg\bullet kg^{-1}$					Force during dynamic MTP 90% 1RM: r = 0.69 120% 1RM: r = 0.74
Nuzzo et al. (49)	12 division I collegiate athletes 1RM PC = 1.28 $kg\bullet kg^{-1}$ 1RM Squat = 1.91 $kg\bullet kg^{-1}$			PRFD CMJ PP: r = 0.65		
Kraska et al. (41)	41 female and 22 male collegiate athletes			PRFD SJ: r = 0.48 SJ20: r = 0.66 CMJ: r = 0.43 CMJ20: r = 0.62		
Whittington et al. (72)	7 NCAA Division I track and field athletes					Ball throw distance: r = 0.78
Khamoui et al. (40)	19 recreationally trained men					RFD50 & high pull PV: r = 0.56 RFD100 & high pull PV: r = 0.56
West et al. (71)	39 professional rugby league		PRFD 10 m: r = -0.66	PRFD CMJ height: r =		

	players			0.39		
Beckham et al. (7)	12 collegiate-national level weightlifters	RFD200 Snatch: r = 0.65 Combined Total: r = 0.60 RFD250 Snatch: r = 0.78 Clean & Jerk: r = 0.72 Combined Total: r = 0.75				
Thomas et al. (64)	14 collegiate team sport athletes		PRFD 5 m: r = -0.58 20 m: r = 0.71		PRFD 505mod: r = -0.57	
Wang et al. (69)	15 collegiate rugby players		5 m: PRFD: r = -0.54 RFD30: r = 0.57 RFD50: r = 0.53		Pro agility: PRFD: r = -0.52 RFD30: r = 0.52 RFD50: r = 0.53 RFD90: r = 0.53 RFD100: r = 0.52	

PRFD = Peak RFD; RFD30 = Mean RFD between 0-30 ms; RFD50 = Mean RFD between 0-50 ms; RFD90 = Mean RFD between 0-90 ms
RFD100 = Mean RFD between 0-100 ms; RFD200 = Mean RFD between 0-200 ms; RFD250 = Mean RFD between 0-250 ms; PV = Peak Velocity

Table 4: Relationships between time specific impulse and performance in other activities

Author(s)	Subjects	Sprint	Jump	Change of Direction
Thomas et al. (64)	14 collegiate team sport athletes	Imp100 5 m: r = -0.71 20 m: r = 0.75 Imp300 5 m: r = -0.74 20 m: r = 0.78		Imp100, 505mod: r = -0.58 Imp300, 505mod: r = -0.62
Thomas et al. (67)	22 collegiate team sport athletes		Imp100 SJ PF: r = 0.57 SJ PP: r = 0.60 CMJ PF: r = 0.64 CMJ PP: r = 0.51 Imp200 SJ PF: r = 0.56 SJ PP: r = 0.59 CMJ PF: r = 0.63 CMJ PP: r = 0.50 Imp300 SJ PF: r = 0.58 SJ PP: r = 0.60 CMJ PF: r = 0.63 CMJ PP: r = 0.49	
Imp100 = Impulse over 100 ms; Imp200 = Impulse over 200 ms; Imp300 = Impulse over 300 ms SJ = Squat Jump; CMJ = Countermovement Jump; PF = Peak Force; PP = Peak Power				

Table 5: Reported Testing and Data Analysis Procedures

Author(s)	Knee Angle	Hip Angle	Sampling Frequency	Onset Threshold	Scaling	Smoothing & Filtering	RFD Calculation
Haff et al. (33)	144 ± 5°	145 ± 3°	500 Hz	---	Net Force	---	PRFD (2 ms window)
Stone et al. (60)	140-145°	---	600 Hz	---	Net Absolute, Relative and AS	---	PRFD (1.7 ms window)
Haff et al. (30)	127-145° *	---	600 Hz	---	Net Force	---	PRFD (1.7 ms window)
McGuigan et al. (47)	130°	---	500 Hz	---	Absolute	---	PRFD (2 ms window)
Kawamori et al. (39)	141±10°	124±11°	500 Hz	---	---	---	PRFD (2 ms window)
Haff et al. (31)	127-145° *	---	600 Hz	---	Net Force	---	PRFD (1.7 ms window)
Nuzzo et al. (49)	140°	---	1000 Hz	---	Ratio	---	Mean RFD
Winchester et al. (74)	130°	---	---	---	Net	---	---
Winchester et al. (73) #	---	---	---	---	---	---	---
McGuigan & Winchester (45)	130°	---	960 Hz	---	---	---	--- Assumed peak due to the values
Kraska et al. (41)	120-135°	170-175° ¥ In line with Haff et al (1997)	1000 Hz	---	Absolute & AS	---	--- Assumed peak due to the values
Whittington et al. (72)	120-135° 'Self-selected'	170-175° 'Self-selected'	1000 Hz	---	---	---	PRFD (1 ms window)
McGuigan et al. (46)	130°	---	960 Hz	---	--- Assumed	---	--- Assumed mean

					Net due to the values		due to the values
West et al. (71)	120-130˚ ¥ In line with Haff et al (2005), Stone et al (2004)	---	1000 Hz	5SD of mean force after trigger	Net	Dual pass Butterworth filter (low pass, 20 Hz cut-off)	PRFD (1 ms window)
Crewther et al. (16)	120-130˚ ¥ In line with Haff et al (2005), Stone et al (2004)	---	1000 Hz	---	Net	Dual pass Butterworth filter (low pass, 20 Hz cut-off)	PRFD (1 ms window)
Beckham et al. (6)	¥ In line with Haff et al. (1997) and Kraska et al. (2009)	¥ In line with Haff et al. (1997) and Kraska et al. (2009)	1000 Hz	---	Absolute & AS	4th Order Butterworth low pass filter 100 Hz	Not included
Beckham et al. (7)	120-135°	175°	1000 Hz	---	Absolute, Ratio & AS	4th Order Butterworth low pass filter 100 Hz	Mean & PRFD (1 ms window)
Sheppard et at. (56)	130°	155-165°	600 Hz	---	Net	---	Not included
Comfort et al. (11)	120°, 130°, 140°, 150° & Self-selected (133 ± 3°)	125°, 145° & Self-selected (138 ± 4°)	600 Hz	40 N	Absolute	---	PRFD (1.7 ms window)
Thomas et al. (64)	Self-selected	Self-selected	600 Hz	---	Absolute	4th Order Butterworth low pass filter 16 Hz	PRFD (1.7 ms window)
Thomas et al. (67)	Self-selected	Self-selected	600 Hz	---	Absolute & Relative	4th Order Butterworth low pass filter 16 Hz	PRFD (1.7 ms window)

Thomas et al. (66)	Self-selected	Self-selected	600 Hz	---	Absolute	4th Order Butterworth low pass filter 16 Hz	Not included
Haff et al. (32)	140.0 ± 6.6°	137.6 ± 12.9°	1000 Hz	---	Net	Rectangular smoothing with a moving half-width of 12	PRFD (20 ms window) $RFD_{30, 50, 90, 100, 150, 200, 250}$
Secomb, et al. (52)	125-140°	---	600 Hz	---	Absolute and Relative	---	Not included
Secomb et al. (53)	125-140°	---	600 Hz	---	Absolute and Relative	---	Not included
Secomb et al. (54)	--- Stated similar to Haff et al. (2005)	--- Stated similar to Haff et al. (2005)	600 Hz	---	Absolute and Relative	---	Not included
Tran et al. (68)	--- Stated similar to Haff et al. (1997)	--- Stated similar to Haff et al. (1997)	600 Hz	---	Absolute and Relative (Assumed Net due to the values)	4th Order Butterworth low pass filter 10 Hz	
Spiteri et al. (58)	140°	140°	2000 Hz	---	Relative	---	$RFD_{30, 50, 90, 100}$
Sjokvist et al. (57)	--- States in line with Stone et al. (2004)				Absolute and Relative	---	Not included
Welch et al. (70)	No specific detail provided other than bar positioned at mid-thigh				Relative	---	Not included
Wang et al. (69)	Self-selected	Self-selected	1000 Hz	---	Net	---	PRFD (20 ms window) $RFD_{30, 50, 90, 100, 150, 200, 250}$
Mangine et al.	Self-selected	Self-selected	1000 Hz	---	Net	---	PRFD (20 ms

(44)							window) $RFD_{30, 50, 90, 100, 150, 200, 250}$
Halperin et al. (34)	130-140°	Not stated	1000 Hz	---	---	---	Not included
Dos'Santos et al. (22)	Self-selected	Self-selected	2000 Hz (down-sampled to 1500, 1000 & 500 Hz)	75 N	Absolute	20 ms moving average	RFD_{100} RFD_{150} RFD_{200}
Bartolomei et al. (4)	140°	125°	1000 Hz	---	Absolute	---	PRFD (20 ms window)
James et al. (38)	141.9 ± 4.3°	139.2 ± 4.1°	1000 Hz down sampled to 100 Hz to compare to strain gauge	20 N	Net	4th Order Butterworth low pass filter 10 Hz	PRFD (20 ms window) $RFD_{30, 50, 90, 100, 150, 200, 250}$
De Witt et al. (18)	144 ± 3°	137 ± 3°	1000 Hz	---	--- Assumed Net due to the values	---	PRFD (20 ms window) $RFD_{30, 50, 90, 100, 150, 200, 250}$
Dos'Santos, Thomas et al. (24)	137-146° ¥	140-149° ¥	1000 Hz	40 N	Absolute	---	Not included
Dos'Santos, et al. (21)	Self-selected	Self-selected	1000 Hz	2.5% BW, 5% BW, 10% BW, >75 N, **5 SD BW**	Absolute	---	RFD_{100} RFD_{150} RFD_{200}
Beckham et al. (8)	125°	125° & 145°	1000 Hz	---	Absolute & AS	2nd Order Butterworth low pass filter 10 Hz	Not included
Oranchuk et al. (50)	135-145°	---	1000 Hz	2.5% of mean body mass, based on force-time data	Relative	4th Order Butterworth filter, with 20 Hz cut-off	PRFD (20 ms window)

Dobbin et al. (20)	140˚	Self-selected, shoulder above the bar (as described by Thomas et al., 2015)	1200 Hz	---	Net relative and AS	---	Not included
Beattie et al. (5)	131 ± 9˚	---	1000 Hz	---	Relative	---	Not included
Dos'Santos et al. (26)	145˚	145˚ & 175˚	1000 Hz	5 SD BW	Net	Unfiltered	PRFD RFD_{100} RFD_{150} RFD_{200}
Leary et al. (42)	142 ± 7°	146 ± 11°	1000 Hz	---		Rectangular smoothing with a moving half-width of 12	PRFD $RFD_{30, 50, 90, 100, 150, 200, 250}$

--- = not stated
¥ = Incorrectly cites joint angles 'in line with previous research' when the referenced studies used different joint angles
Net Force = Gross Force – Body Weight
PRFD = Peak Instantaneous RFD (the greatest rate of change in force between two tangential points; the window differs based on sampling frequency)
Mean force (Change in force / change in time from onset of force production to time to peak force)
RFD_{100} = subscript numbers refer to the epoch for mean RFD
*Based on knee angle achieved during the 2nd pull phase of the clean for each individual
#Published abstract
¥ Self-selected to replicate the start of the second pull
BW = Body weight (during the initial period of quiet standing), SD = standard deviation

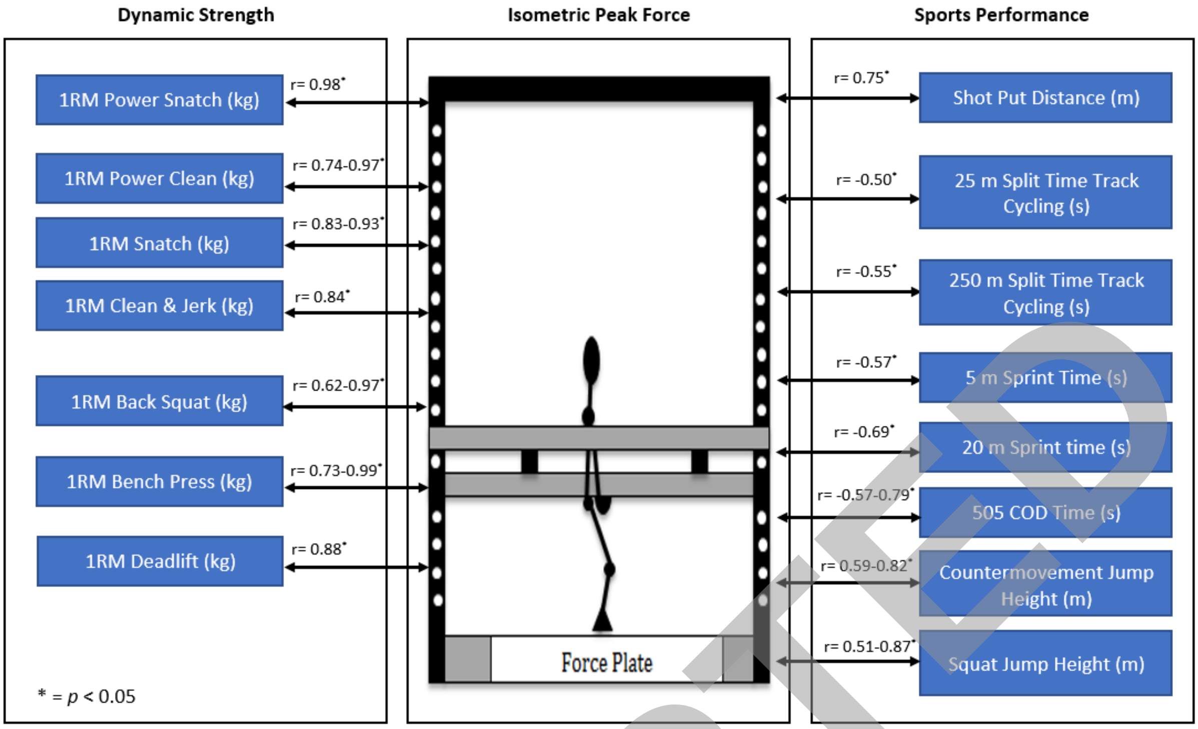


Figure 1: Relationships between isometric mid-thigh pull peak force and performance in other tasks (References in Table 1)

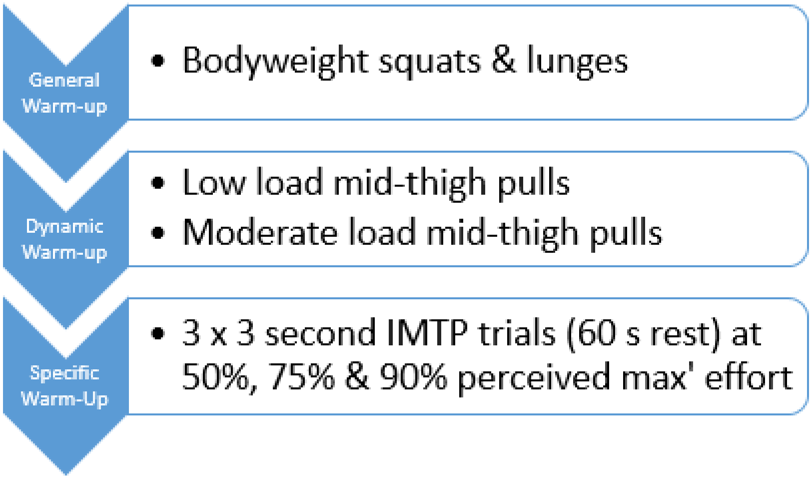
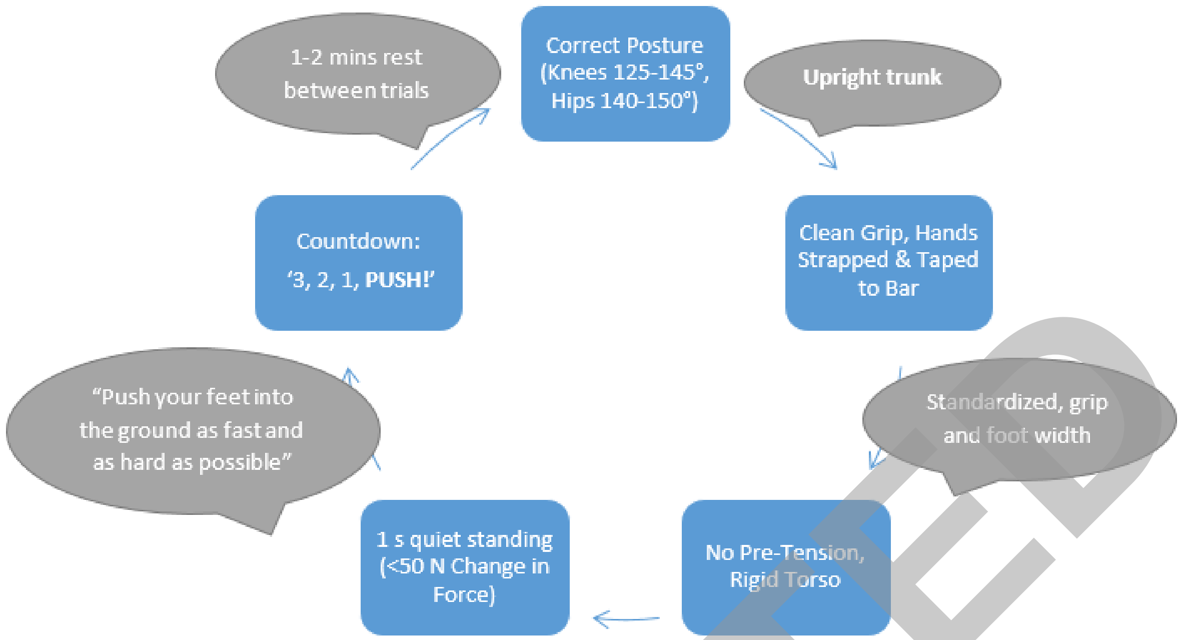


Figure 3: Standardized Warm Up Procedure



Acceptable trials <250 N difference in peak force, minimal pre-tension (<50 N) or countermovement at the start

Figure 4: Standardized isometric mid-thigh pull testing procedure

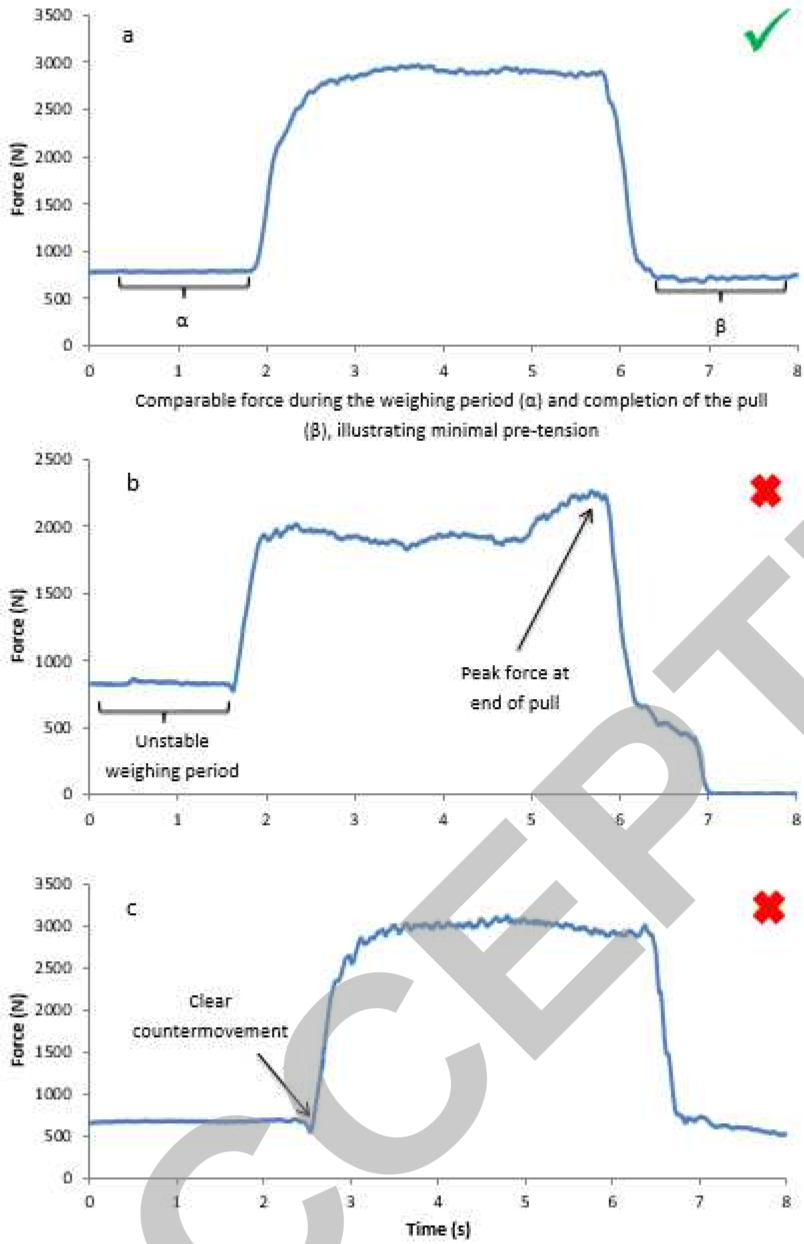


Figure 5: Examples of acceptable and unacceptable isometric mid-thigh pull force-time traces