1   **Standardization and methodological considerations for the Isometric Mid-Thigh Pull**

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26   **Abstract**

27   The isometric mid-thigh pull (IMTP) is commonly used to assess an athlete's force generation

28   ability. This test is highly reliable and is simple and relatively quick to perform. The data that

29   can be determined from the force-time curves generated by the test have been shown to be

30   closely related to performance capacities in a variety of dynamic athletic tasks. However,

31   within the scientific literature there are inconsistencies in the data collection procedures and

32   methods used for data analysis that may impact the resultant output and the ability to compare

33   and generalize results. Therefore, the primary aim of this review is to identify the differences

34   in IMTP testing procedures and data analysis techniques, while identifying the potential impact

35   this may have on the data collected. The secondary aim is to provide recommendations for

36   the standardization of testing procedures to ensure that future IMTP data is of maximal benefit

37   to practitioners and researchers.

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39   **Introduction**

40   Maximal strength underpins performance in many athletic tasks (15, 55, 63) and as such,

41   monitoring strength, usually via repetition maximum (RM) testing, is commonly performed by

42   practitioners and researchers. While RM testing is reliable (12, 24, 28), it can be perceived as

43   fatiguing, posing an increased potential for injury risk, and only providing information related

44   to the maximal load lifted. In contrast, isometric testing, such as the isometric mid-thigh pull

45   (IMTP), is potentially safer (18), less fatiguing, and allows for the quantification of peak force

46   (PF), force at a variety of epochs, and can provide several measures of the rate of force

47   development (RFD) (11, 21, 26, 30, 32, 33). The diagnostic ability of these measures may be

48   of importance when considering time constrained tasks within sports, such as jumping,

49 sprinting and change of direction. Importantly, the IMTP has been shown to be highly reliable

50 both within and between sessions, with low variability and low measurement error (8, 11, 18,

51 24, 26, 27, 32).

52 Performance in the IMTP has been associated with performance in numerous athletic tasks

53 (7, 18, 30, 33, 40, 41, 45, 46, 49, 59, 64, 66, 67, 69, 72, 73). Specifically, absolute PF has

54 been associated with weightlifting performance (7, 30), 1RM squat and power clean (45-47,

55 49, 59, 69, 73), 1RM deadlift (18), vertical jump performance (39-41, 53, 60, 64, 67), short

56 sprint and change of direction times (59, 64), sprint cycling performance (60), and throwing

57 performance (72) (Table 1). In contrast, West et al. (71) reported no meaningful relationships

58 between absolute PF and short sprint times or jump height, although they did observe large

59 correlations between relative PF (PF/body weight) and these variables in rugby league

60 players. Similarly, Nuzzo et al. (49) reported only a small relationship between absolute PF

61 and jump height but a large relationship between relative PF and jump height (Table 1). The

62 range of associations between PF and performance in other tasks is summarised in Figure 1.

63 Researchers have also reported relationships between allometrically scaled PF and

64 performance in athletic tasks (60, 72), demonstrating similar correlations to those observed

65 when ratio scaling is used (60).

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

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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

Dynamic Strength   **Isometric Peak Force**   **Sports Performance**

1RM Power Snatch (kg) — r= 0.98* — Shot Put Distance (m) — r= 0.75*

1RM Power Clean (kg) — r= 0.74-0.97* — 25 m Split Time Track Cycling (s) — r= -0.50*

1RM Snatch (kg) — r= 0.83-0.93* — 250 m Split Time Track Cycling (s) — r= -0.55*

1RM Clean & Jerk (kg) — r= 0.84* — 5 m Sprint Time (s) — r= -0.57*

1RM Back Squat (kg) — r= 0.62-0.97* — 20 m Sprint time (s) — r= -0.69*

1RM Bench Press (kg) — r= 0.73-0.99* — 505 COD Time (s) — r= -0.57-0.79*

1RM Deadlift (kg) — r= 0.88* — Countermovement Jump Height (m) — r= 0.59-0.82*

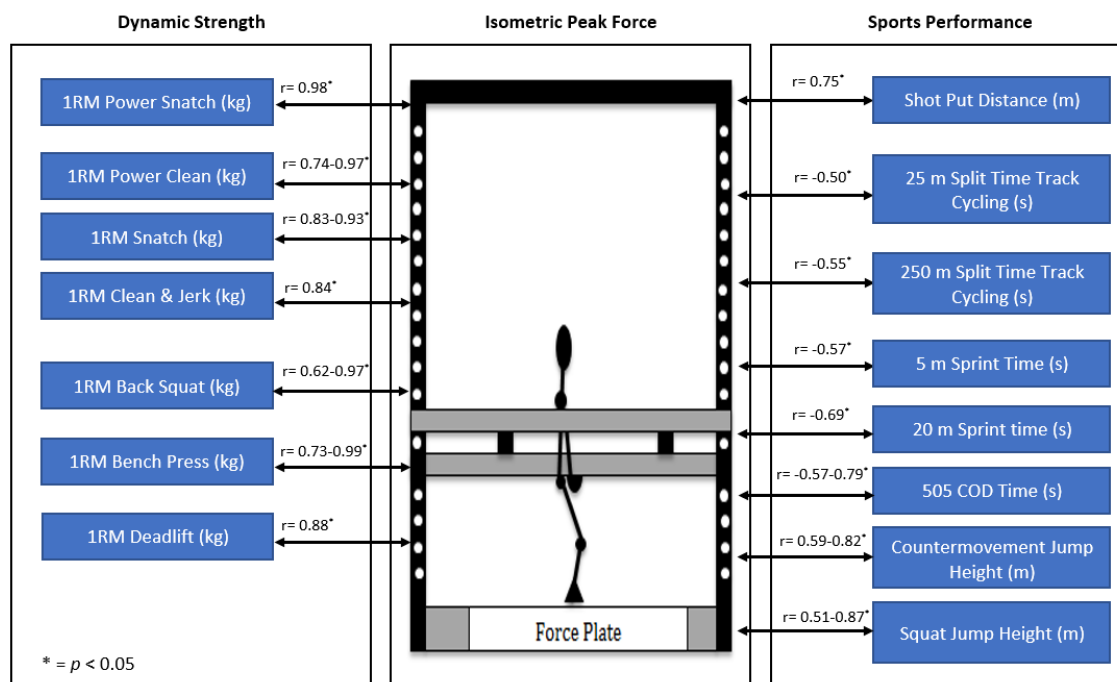Squat Jump Height (m) — r= 0.51-0.87*

Force Plate

* = $p < 0.05$

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

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).

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

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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* *ASF150* & Mean Club Head Speed: r = 0.46 *ASF150* & 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					

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97 Equivocal results regarding the relationships between measures of RFD and performance in dynamic athletic tasks have been reported in the

98 scientific literature. When examining how the RFD is quantified two main methods exist within the literature (32). The first method is to quantify

99 the peak RFD (PRFD) that occurs during the IMTP with a predefined moving window, most typically lasting between 2-40 ms (32) (Table 3).

100 When this method is utilized for analyzing the force-time curve conflicting results exist within the scientific literature with some authors reporting

101   significant relationships between the RFD and dynamic performance activities (30, 33, 39, 41),

102   while others report no meaningful relationship with 1RM performance (7, 45-47), or SJ and

103   CMJ performances (40, 49, 67). These difference may be attributable to the moving window,

104   with Maffiuletti et al. (43) cautioning against the use of short windows (e.g. 2 ms) as they may

105   be too sensitive to unsystematic variability and therefore less reliable. The second method for

106   evaluating the RFD is to examine time dependant epochs (32). The use of time dependent

107   epoch has been shown to be an effective method for examining the RFD during the IMTP and

108   relating it to various sports performance tasks. For example, Spiteri et al. (58) report that

109   athletes who produce higher RFD to 90 ms and 100 ms are able to demonstrate faster agility

110   times during a 45 ˚ cutting task. One possible explanation why some RFD measures relate to

111   dynamic performance activities and others do not is the method of calculation and reliability of

112   the method. For example, Haff et al. (32) have shown that the only PRFD measure that is

113   reliable is when a 20 ms moving window is used, supporting previous suggestions by

114   Maffiuletti et al. (43). Conversely, using time dependent epochs such as 0-90 ms, 0-150 ms,

115   0-200 ms and 0-250 ms to calculate the mean RFD across the specific duration produces

116   much more reliable results and generally have better relationships to dynamic performance

117   measures. Therefore, it is generally recommended that using time specific RFD epochs is

118   warranted when using the IMTP as a performance diagnostic tool (32).

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126 **Table 3: Relationships between RFD and performance in other activities**
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Author(s)	Subjects	1RM	Sprint	Jump	Change of Direction	Other
Haff et al. (33)	8 trained (>2 years) men 1RM PC = 1.21 kg•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•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•kg^{-1} 1RM Squat = 1.91 kg•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 players		PRFD 10 m: r = -0.66	PRFD CMJ height: r = 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

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129 Another method for analysing the force-time curve derived from an IMTP is to examine the isometric impulse (67, 68). For example, impulse

130 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

131 direction times (64), peak force and power during the SJ and CMJ (68) (Table 4). While determining the isometric impulse of various epochs

132 within the force-time curve achieved during the IMTP yields useful information much more research is needed to understand how best to utilise

133 this measurement in a sports performance monitoring program.

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

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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				

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139   The PF achieved during the IMTP has also been used to monitor adaptations to training (5,

140   36, 50, 51, 57, 70, 74), with some authors also including RFD (36, 51, 52, 74). PF and peak

141   RFD have also been used in an attempt to identify levels of fatigue or recovery (4, 29, 35, 44).

142   More recently researchers have started to investigate the potential of the IMTP to investigate

143   between-limb asymmetries, using dual force platforms (1-3) and a unilateral stance IMTP (25,

144   65). Additionally, the PF during the IMTP has been divided by the PF during a SJ or CMJ, to

145   calculate the dynamic strength index (DSI; ratio of PF during the CMJ or SJ and IMTP PF), in

146   attempt to identify if an athlete needs to focus more on maximal force production or rapid

147   dynamic force production (14, 52, 54, 56, 66).

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149   **Variation in Testing and Data Analysis Procedures**

150   Unfortunately, there is substantial variation across testing protocols reported within the

151   scientific literature, including differences in knee and hip joint angles (120-150° and 124-175°,

152   respectively), sampling frequency (500-2000 Hz), pull onset identification thresholds including

153   absolute (20-75 N) and relative (2.5-10% body weight) threshold values, and smoothing and

154   filtering approaches, with some authors not stating hip angles, thresholds or filtering

155   procedures (Table 5). In addition, if practitioners or researchers are intending to use published

156   values for comparison they should be mindful that some data is presented as net force (gross

157   force – body weight) while others report gross measures, along with ratio and allometric

158   scaling used in some studies. These two latter approaches may impact the results less, as

159   allometric scaling uses an exponent related to body mass (13) although allometric scaling will

160   reduce the resultant values compared to ratio scaling, with greater variation introduced

161   depending on the exponent used (Table 5).

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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 Net due to the values		Assumed mean 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	PRFD (1.7 ms window)

						low pass filter 16 Hz	
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)

Study							RFD$_{30, 50, 90, 100, 150, 200, 250}$
Mangine et al. (44)	Self-selected	Self-selected	1000 Hz	---	Net	---	PRFD (20 ms 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

167   Numerous authors have suggested that the posture adopted during the IMTP should replicate

168   the start of the second pull phase of the clean, (30, 31, 33, 60); however, only two studies

169   have actually assessed the participants knee joint angles during the clean and then adopted

170   these angles during the IMTP (30, 31). This is most likely due to time and practicality of

171   assessing specific joint angles during the clean prior to performing the IMTP, especially when

172   assessing large squads of athletes. Interestingly, hip joint angles were not reported within

173   these two studies (30, 31).

174   Due to the variety of knee and hip joint angles reported within the literature, Comfort et al. (11)

175   investigated a range of knee (120°, 130°, 140°, 150°) and hip (125°, 145°) joint angles, along

176   with self-selected posture (knee 133±3°, hip 138±4°) based on the athletes preferred position

177   to start the second pull of a clean, which is what the posture adopted during the IMTP was

178   originally based on (33). The results of the study indicated that there were no significant or

179   meaningful differences in PF, PRFD or impulse between postures, although the preferred

180   (self-selected) posture demonstrated the highest reliability and the lowest measurement error.

181   In contrast, Beckham et al. (6) found that powerlifters produced greater PF during an isometric

182   testing with a vertical torso compared to a deadlift-specific body position at the same bar

183   height, described as being a "relatively straight legged position and somewhat bent over the

184   bar". The authors suggested that the upright position may have provided a mechanical

185   advantage and a posture more optimal for force production against the bar. In another study,

186   Beckham et al. (8) compared the effects of different hip joint angles (125° vs. 145°), while

187   standardizing the knee joint angle (125°) reporting meaningful and significantly higher PF and

188   force at different epochs (50, 90, 200, 250 ms) in the more upright (145°) position, especially

189   in subjects with greater experience in performing weightlifting exercises and their derivatives,

190   in contrast to Comfort et al. (11). Interestingly, Beckham et al. (8) reported small changes in

191   joint angles throughout the execution of the test and based on these observations recommend

192   that in the future researchers and practitioners should adopt standardized knee and hip angles

193   of 120-135° and 140-150°, respectively.

194   More recently, Dos'Santos et al. (26) compared hip joint angles of 145˚ and 175˚ with a

195   standardized knee joint angle of 145˚, finding greater time specific force values and RFD at

196   predetermined epochs, with a 145˚ hip angle (Table 5). The hip angle of 175˚ previously

197   reported by Kraska et al. (41) and replicated by Beckham et al. (6) actually refer to trunk angle

198   relative to vertical, to ensure an upright trunk (forward lean of 5˚ from vertical), exhibiting an

199   upright trunk as previously described (30, 31, 33, 60) rather than a 175˚ hip angle as used by

200   Dos'Santos et al. (26). The authors of a recent meta-analysis also highlight the fact the

201   practitioners should carefully consider the specific protocol, including joint angles, to ensure

202   repeatability of the measures (27).

203   While adopting standardized knee and hip angles during the IMTP may seem logical, this

204   practice may place athletes in a sub-optimal pulling position, due to the range of angles

205   reported across individuals for the second pull phase of the clean (30, 31). Therefore, it is best

206   to consider the individual athletes' appropriate second pull position and then quantify the knee

207   and hip angles. This practice allows for the individual athlete's anthropometrics to be

208   considered and allows them to assume an optimal pulling position, in line with the range of

209   joint angles recommended by Beckham et al. (8). Once the pulling position is established then

210   it is recommended that practitioners and researchers ensure that the individual starting

211   postures are replicated between trials and testing sessions. Joint angles should be assessed

212   prior to the commencement of the pull due to slight changes in joint angles during the pull (8).

213   Haff et al. (32) suggest using minimal pre-tension prior to initiation of the pull, as this is likely

214   to impact both time specified force and RFD, with Dos'Santos et al. (26) recently reporting that

215   the 175˚ hip angle results in significantly higher 'body weight' due to increased pre-tension,

216   compared to a 145˚ hip angle, which may have contributed to in the differences in time specific

217   force values and RFD that were reported. Similarly, Maffiuletti et al. (43) suggested that pre-

218   tension is undesirable when assessing isometric RFD, albeit with a focus on single joint

219   assessment; it would, therefore, be advantageous to visually inspect the force-time data pre

220   and post isometric pull, to ensure that there are no differences in force, which should represent

221   body weight.

222   Interestingly, numerous authors state that they have adopted the postures previously reported

223   by other researchers, but in fact report different angles to those stated in the studies that they

224   cite, or cite multiple researchers who reported different postures (Table 5). These differing

225   postures are most likely related to individual athlete anthropometric profiles. It is therefore

226   important that researchers carefully report and justify their choice of joint angles, but more

227   importantly, standardize these between trials and testing sessions.

228   Other researchers have used strain gauge based equipment, with the handle attached via a

229   chain (16, 17, 37, 38, 48) with a range of sampling frequencies (100-133 Hz (17, 37, 38)) and

230   joint angles (knee 120-130˚ (17), 142±4˚(38), 143±7˚ (37), 160˚ (48); hip 139±4˚ (38), 144±5˚

231   (37)). However, findings of two research groups that compared strain gauge systems to a

232   force platform demonstrated that the strain gauge significantly underestimated PF, by ~8%

233   (38) to ~10% (20). Additionally, James et al. (38) found that measures of RFD did not meet

234   acceptable standards of reliability. While such systems can measure PF, which can be ratio

235   or allometrically scaled, there does not seem to be an effective way to accurately measure or

236   calculate RFD, and are therefore not recommended if practitioners have access to a force

237   platform.

238

239   **Recommendations for Correct IMTP Assessment**

240   Due to the noticeable variations in assessment procedures, including posture, sampling

241   frequency, and methods of calculating specific variables (namely use of different sampling

242   frequencies, onset thresholds, and the method for the calculation of RFD), we suggest

243   appropriate standardization of all testing procedures for the IMTP. Such standardization

244   should permit more meaningful comparisons of individual performances between testing

245   sessions, comparisons between athletes and more effective comparisons between published

246 studies. Standardization should also include the verbal cues as attentional focus has been

247 shown to affect force production, with an external focus of 'push as hard and fast as possible'

248 resulting in greater PF compared to an internal focus (34).

249

250 **Recommended Testing Procedures**

251 Prior to initiation of IMTP testing, the bar height necessary to obtain the correct body position

252 should be determined. This should be an iterative process in which the athlete starts with a

253 bar height that allows the athlete to assume a body position that replicates the start of the

254 second pull position during the clean. The bar height should then be adjusted up or down to

255 allow the athlete to obtain the optimal knee (125-145°) and hip (140-150°) angles (6, 8, 26).

256 The body position should be very similar to the second pull of the clean and the clean grip

257 mid-thigh pull exercise (19): upright torso, slight flexion in the knee resulting in some

258 dorsiflexion, shoulder girdle retracted and depressed, shoulders above or slightly behind the

259 vertical plane of the bar, feet roughly centred under the bar approximately hip width apart,

260 knees underneath and in front of the bar, and thighs in contact with the bar (close to the

261 inguinal crease dependent on limb lengths) (Figure 2). When making joint measurements, the

262 athlete should ensure that no tension is applied to the bar but that all "slack" (e.g. elbow flexion,

263 shoulder girdle elevation/protraction) is removed from the body, as this would result in a

264 change in joint angles during the maximal effort which is undesirable (8).
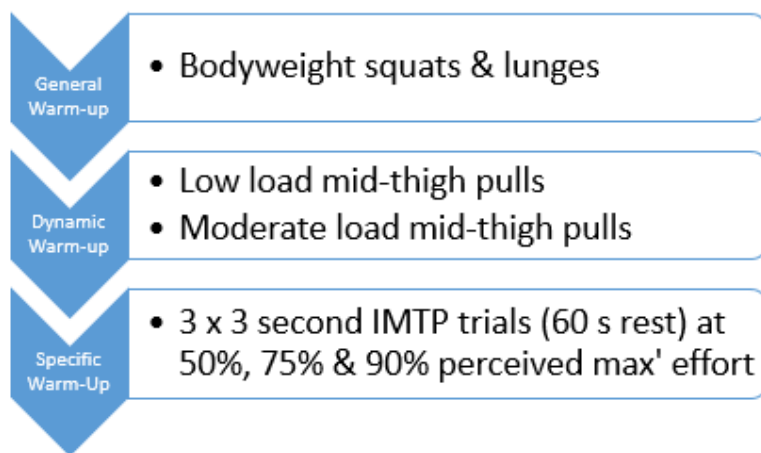
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Figure 2: Correct posture for the isometric mid-thigh pull, illustrating an upright trunk, replicating the start position of the second pull of the clean

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

287 optimal amount of familiarization has not yet been reached, nearly all IMTP studies use some

288 familiarization.

289 Athletes should complete some manner of standard generalized warm-up (62). While there is

290 variability in the generalized warm-up chosen among studies, most studies use a warm-up

291 that incorporates clean derivatives, such as the dynamic mid-thigh pull, and should thus be a

292 component of the standard warm-up (7, 21, 24, 32, 33). Submaximal trials of the IMTP are

293 also recommended prior to maximal effort trials (e.g. 3 seconds each of: 50% maximal effort,

294 75% maximal effort, 90% maximal effort, separated by 60 seconds rest). During this time, the

295 athlete should be secured to the bar using lifting straps and athletic tape to ensure that grip

296 strength is not a limiting factor (Figure 3) (30, 33).

General Warm-up
- Bodyweight squats & lunges

Dynamic Warm-up
- Low load mid-thigh pulls
- Moderate load mid-thigh pulls

Specific Warm-Up
- 3 x 3 second IMTP trials (60 s rest) at 50%, 75% & 90% perceived max' effort

297 Figure 3: Standardized Warm Up Procedure

298 For each of the maximal effort trials, standardized instructions should be given to the athlete

299 of some iteration of "push your feet into the ground as fast and as hard as possible" to ensure

300 that both maximal RFD and PF are obtained (10, 34). It is essential that athletes understand

301 that the focus is to drive the feet directly into the force platform and not attempt to pull the bar

302 with the arms, or rise up on to their toes. The athlete should get into the correct body position

303 for the IMTP, using just enough pre-tension to achieve the correct body position and remove

304 "slack" from the body, but without any more pre-tension than is necessary to get the "quiet

305 standing" necessary for a stable force baseline (43). This can be verified by monitoring the

306   athlete's body positioning and ensuring the force trace created by the athlete is both similar to

307   body mass and steady, with trials where a change in force >50 N occurs during this period

308   rejected (21). This should be explained to the athletes and they should be encouraged to stay

309   as still as possible during this period to accurately determine body weight and onset threshold.

310   A countdown of "*3, 2, 1, PULL!*" gives the athlete sufficient warning to be ready to give a

311   maximum effort and provides at least one second of quiet standing to enable the identification

312   of the onset of the pull (Figure 5a). Strong verbal encouragement from researchers and

313   teammates ensures that the athlete gives a maximum effort (9). A minimum of two trials should

314   be collected, provided that each of those trials have no errors by the athlete (e.g.

315   countermovement, excessive pre-tension, leaning on the bar prior to the pull (Figure 4). With

316   increasing PF, additional trials should be performed, until the PF values of the trials are

317   separated by <250 N (30, 33). It is noted, however, that a percentage of peak force may be

318   advantageous as an absolute value will affect stronger and weaker athletes differently,

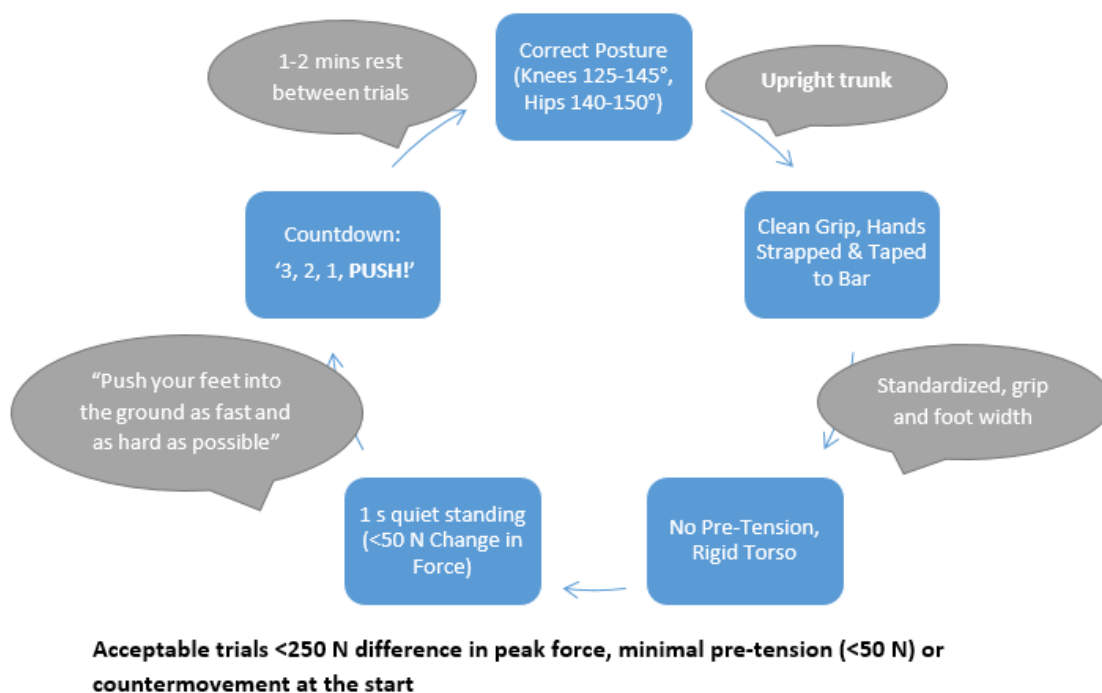319   although the exact effect of this has not been investigated.

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

320

321   Visual inspection of the force-time curves during testing can easily be used to determine if the

322   trials are acceptable, or if additional trials should be performed. In addition to the trials being

323   within 250 N between attempts, trials should be repeated if there is not a stable weighing

324   period (clear fluctuation in the force-time data) or a clear countermovement prior to the

325   initiation of the pull (Figure 5c), as this will interfere with accurate identification of the initiation

326   of the pull (19), or if the PF occurs at the end of the trial (Figure 5b). It is also important to

327   check that the force during the initial period of quiet standing (in the ready position, strapped

328   to the bar, immediately prior to commencing the pull) represents body weight, and therefore

329   no prior tension has been applied (Figure 5a) as this will interfere with pull onset identification
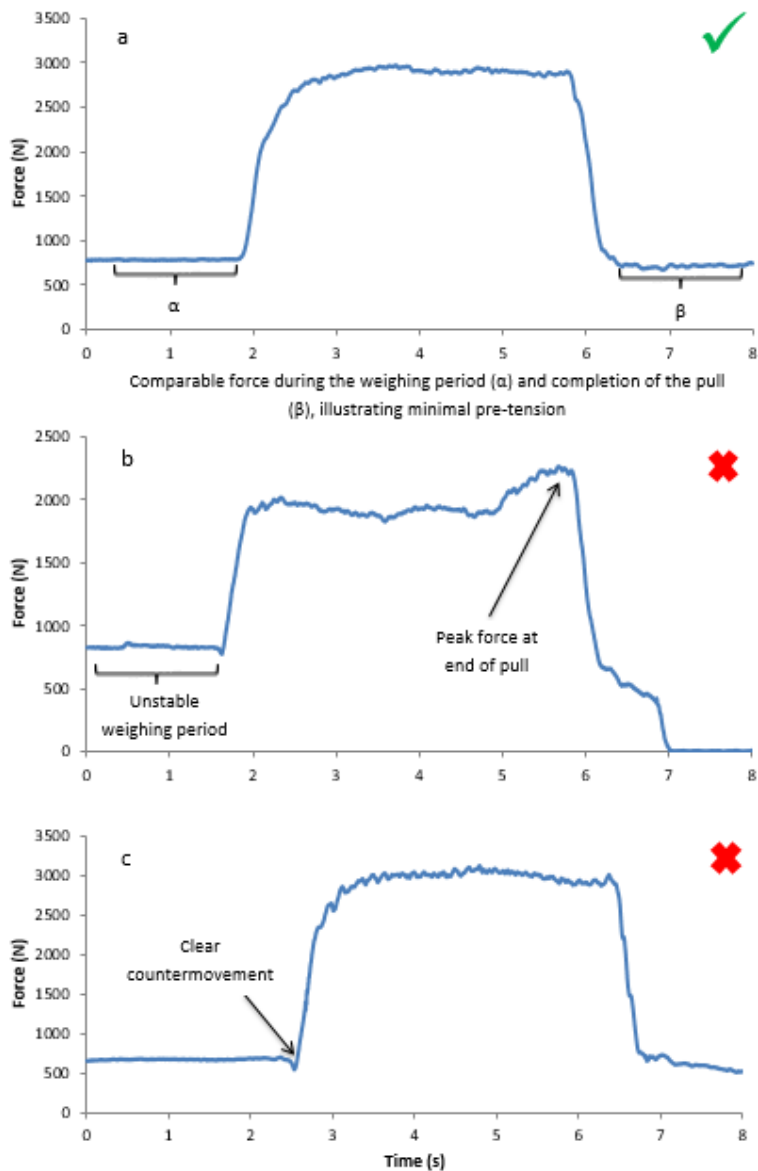
330   (19).

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

331

Recommended Data Analysis and Reporting

333   Collection of IMTP force-time data can be compiled accurately with a sampling frequency as

334   low as 500 Hz , but if higher sampling frequencies can be used then they are preferred as they

335   may increase the accuracy of time dependent measures (21). Specifically, the utilization of

336   frequencies ≥1000 Hz are recommended especially if early force-time variables are of interest

337   (e.g. force at 50 or 100 ms) (21). There are not enough data for a consensus regarding optimal

338   filtering and/or smoothing methods for the IMTP (23); although unfiltered data has been

339   suggested as optimal for analysis of countermovement jump performance (61) and where

340   possible, unfiltered data for isometric testing (23, 43). It is therefore suggested that unfiltered

341   and non-smoothed data is used for subsequent analysis (23), as most of the RFD and impulse

342   characteristics are dependent upon an accurate determination of the start of the pull (21),

343   although data from portable force platforms may exhibit greater 'noise' and warrant smoothing.

344   Accurate identification of the start of the inflection point is often achieved using automated

345   methods - we recommend using 5 standard deviations of body weight during an initial one

346   second weighing period prior to the (usually one second) of quiet standing (in the ready

347   position, strapped to the bar, immediately prior to commencing the pull) as the threshold for

348   determining the onset of the pull (21), although this may vary with technical idiosyncrasies of

349   different force platforms (e.g. noise magnitude). Trials that do not have a stable baseline force

350   trace during the weighing period (change in force >50 N) should be rejected and subsequently

351   another trial should be performed (21, 43) (Figure 5). To facilitate this stable period, it is

352   essential to enforce and practice this during the warm-up / familiarization trials.

353   It is recommended that time-specific RFD epochs (50-, 100-, 150-, 200- and 250 ms commonly

354   reported) should be used when using the IMTP as a sport performance diagnostic tool as

355   these are not only reliable (32), but can be selected specific to the durations relevant to the

356   specific sporting tasks, such as ground contact time during acceleration or peak running

357   speeds. In contrast, maximal strength capabilities can be inferred from PF (Table 1).

358   When reporting results from IMTP testing, it is important that the hip and knee angles used by

359   each athlete, to establish the bar height, be reported (8, 26). Such standardization of posture

360   between trials and testing sessions ensures that data is comparable between sessions, groups

361   of athletes and studies (8, 26). While there is no consensus as to the superiority of either net

362   or gross force values for the IMTP, it is important that researchers report whether body weight

363   was or was not included in the force and impulse values reported (7). Other methodological

364   considerations, such as the method for identifying the onset of the pull (and threshold) (21),

365   methods used for smoothing/filtering force platform data (23), sampling frequency and other

366 aspects of analysis (22), such as the exponent used for allometric scaling, should be reported,

367 as each are important for accurately interpreting results from the study.

368

369

370

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