The isometric mid-thigh pull: a review and methodology – Part 2

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ABSTRACT

The isometric mid-thigh pull (IMTP) is a commonly used test for the assessment of skeletal muscle function in athletes from a wide variety of sports. Although force-generating capacity and rate of force development measured in the IMTP are related to dynamic athletic performance measures, the testing and analysis procedures used can have adverse effects on the magnitude and reliability of the force-time characteristics produced. As such, this review focuses on the correct testing and analysis methodologies to use during IMTP testing

Introduction

The first part of this two-part review of the literature relating to the isometric mid-thigh pull (IMTP) examined the history of the test, along with the relationships between force-time characteristics expressed during the IMTP and common markers of athletic performance. When compared to common laboratory-based isometric testing modalities, the force-time characteristics expressed in the IMTP typically display stronger relationships to dynamic measures of maximum strength and explosive dynamic movements such as sprinting,[51,59] jumping,[50,53] and change of direction.[51] These relationships, however, are reliant on the use of the correct testing methodology, particularly in relation to both the body posture and barbell positions used, along with the reliability of the data analysis procedures subsequently used.

Therefore, the aim of Part 2 of this review is to examine the existing scientific literature in order to better understand the experimental protocols used to perform the IMTP and which methodologies are used in the subsequent data analysis procedures. It is hoped that, by establishing a better understanding of the testing and analysis procedures, practical guidelines can be established that will allow practitioners to employ the test in a reliable and repeatable manner in order to optimise the regular monitoring of athletes.

EQUIPMENT REQUIREMENTS FOR THE IMTP

The IMTP was originally performed within a custom-designed power rack (Sorinex, Irmo, SC), specifically constructed for the performance of both the isometric squat (ISqT) and the IMTP.[24] This rack allowed the adjustment of the immovable barbell (ie, cold rolled steel) in a step-wise manner to any height above a single force plate (Advanced Mechanical Technologies, Newton, MA) through a combination of pins and hydraulic jacks.[24] More recently, the IMTP has been performed utilising various iterations of commercially available portable systems,[10,17,46,47,56,57] or by fixing an Olympic barbell horizontally across the safety pins of a squat rack.[51,53] Furthermore, as the test has evolved it has recently been performed with the use of dual force plates allowing the assessment of potential differences in force-producing asymmetries of the lower body to be identified.[1]

Within the scientific literature utilising the IMTP, there have been various force-plates used, often sampling with differing sampling frequencies.[6,24,57] Typically, the sampling frequency used for collecting force time curve data during the IMTP has been recommended to be a minimum of 1000 Hz.[34,40] McMaster et al[40] recommend the use of a sampling rate of between 1000-2500 Hz for both the IMTP and ISqT,[40] based upon the Nyquist sampling theorem.[41] This theorem states that a sampling frequency of double the highest frequency contained in the signal is required to ensure none of the original analog signal is lost.[41] Sampling below this critical frequency therefore increases the likelihood of important data contained within the original analog signal being lost due to aliasing occurring during the conversion to digital form.[34] This is of particular concern when determining the onset of muscular contraction during isometric trials and analysing time-based epochs of force-time characteristics such as impulse (IMP) and the RFD during the early stages of muscular contraction (ie, IMP0-100, RFD0-50, etc).[34] Furthermore, sampling at a rate below 1000 Hz eliminates the ability to synchronise the force signal to other measurement devices such as EMG, which are often used in diagnostic analyses.[30,34] As the recommended amplifier band setting is 10-500Hz during EMG use, accurate EMG measurement requires a sampling frequency of at least 1000Hz due to Nyquist's Theorem.[30,33]

On many occasions throughout the scientific literature, however, sampling rates of less than 1000 Hz, such as 500 Hz[24] and 600 Hz[46, 47, 51, 53, 56, 57] have been used. Recently, Dos'Santos et al[13] examined the effect of different sampling rates on the force-time curve characteristics derived during performance of the IMTP, with force-time data collected at 2000 Hz and subsequently down-sampled to 1500, 1000, and 500 Hz during further analysis. No significant differences were found between measures of peak force (PF), time-specific force (100, 150, 200 ms) and RFD time-bands (0-100, 0-150, 0-200 ms) regardless of sampling frequency, along with high reliability in each force-time characteristic measured at each frequency.[13] However, as Dos'Santos et al did not examine the effect of sampling rate upon early phases (<100 ms) of RFD, it is still unclear what, if any, effect sampling below 1000 Hz has upon these RFD values. As such, although these data suggest that sampling rates of as low as 500 Hz may be utilised during performance of the IMTP, if a force plate or combination of multiple force plates with a sampling frequency of greater than 1000 Hz are available, then they should be preferentially used, particularly when accurate measurement of time-specific force and RFD outputs during the early stages of force application (<100 ms) are of concern or synchronisation with other measurement devices is required.[34, 40]

EQUIPMENT SET-UP AND PRE-TRIAL INSTRUCTIONS

When undertaking the IMTP, either a customised power rack that allows for the movement of the barbell to any height,[23,24] or a portable isometric rack[10,17,56] that enables stepwise alterations in barbell height, should be used. These systems should allow minimal compliance of both the barbell and power rack,[34] therefore reducing the risk of alterations in joint angles upon force application adversely affecting the results.[6,34] Previous research has demonstrated that instructing the athlete to produce force as hard and as fast as possible results in superior PF and RFD values when compared to simply instructing the athlete to produce force as hard as possible.[25,45] Specific to the IMTP, Halperin et al[25] demonstrated the use of an externally focused instruction to 'push the ground as hard and as fast as you possibly can' results in significantly greater PF values when compared to providing an internally focused instruction to 'contract your leg muscles as hard and as fast as possible'.[25] Therefore, when performing the IMTP, athletes should be instructed to 'pull as hard and as fast as possible', while 'pushing against the ground (ie, the force platform) as hard and fast as possible' which is the pre-test instruction consistently used throughout the literature.[23,24,29,49]

BARBELL POSITION AND BODY POSTURE

Within the literature, there have been several barbell and body positions utilised during performance of the IMTP. The position originally described by Haff et al[24] and subsequently extensively utilised throughout the scientific literature,[3,6,12,13,15,17,27,28,42,48,50] is identical to the position found at the initiation of the second pull of the clean.[22,24] Haff et al[22] confirmed this position matches the one found during dynamic performance of the clean using two-dimensional video analysis. Although the origins of the IMTP test are centred on the second pull position, Comfort et al,[10] McGuigan et al,[37,39] McGuigan and Winchester,[38] and Wang et al[58] suggest the use of a position at the mid-point between the iliac crest and the middle of the patella. Comfort et al[10] reported that provided this barbell position was maintained throughout all trials, no significant differences between force-time characteristics occurred, regardless of changes in either knee- or hip-angle.[10] Beckham et al,[5] however, demonstrated that in powerlifters a higher barbell position, similar to that originally described by Haff et al,[24] produces significantly greater PF than a barbell position just above the knee with a concurrent 'bent over' torso position,[5] similar to the position reported by McGuigan et al.[36] Similarly, Beckham et al[6] recently reported that weightlifters produce greater PF in the position mimicking that of the second pull of the clean when compared to the position suggested by both Comfort et al[10] and Wang et al.[58] Interestingly, Beckham et al[6] also reported that some participants were physically unable to attain the desired body posture using the lower 'mid-thigh' barbell position or substantially shifted their torso position further upright upon trial initiation in a manner similar to the repositioning of an athletes torso during the transition from the first to second pull of the clean.[6] As such, athletes should be monitored for changes in joint angles during performance of the IMTP as this has the potential to adversely affect the force-time characteristics produced.[6,34]

Therefore, based upon the contemporary body of scientific knowledge the starting position of the IMTP should mimic the position achieved at the initiation of the second pull during the clean.[6,24] Generally, in this body posture the barbell is positioned across the upper portion of the thigh, immediately inferior to the pelvis (see Figure 1). Exact hip, knee angle or barbell placements are difficult to recommend as an individual's anthropometrics will exert a large impact on their ideal position. However, when examining the scientific literature, the average knee angle will be approximately 130-145°,[3,23,24,50] whereas the hip angle will be approximately 140-145°.[6,23,24] Some literature has reported the use of a 155-175° hip angle;[3,49] however, this angle describes the trunk angle relative to vertical, not the internal hip angle between the torso and the thigh. The use of a 175° hip angle results in a reclined torso position and adversely affects the force-time characteristics generated when compared to a hip-angle of 145°.[16] Knee- and hip-angles used during testing should be verified and recorded with a hand-held or electronic goniometer and then maintained for all subsequent testing sessions. The athlete's torso should be in an upright position, with the feet positioned roughly hip-width apart and with the same grip as that used during the clean.[6,23,24] As with the maintenance of joint angles between testing sessions, the grip width and foot position should be recorded and then maintained across all trials the individual performs in the IMTP to assist with inter-session reliability. These measurements should be performed during the familiarisation session prior to testing, allowing faster testing of large cohorts of athletes.

WARM-UP PROCEDURES

A short, approximately five-minute dynamic warm-up of general bodyweight movements such as lunges and squats should proceed the specific warm-up. The athlete(s) should then perform at least three sets of 3-5 reps of dynamic mid-thigh pulls (MTP) of increasing submaximal intensity. The load for these dynamic MTPs should be prescribed per percentages (40, 60, 80%) of the athlete's established 1RM power clean[10] or of a perceived/estimated maximum. Barbell height during dynamic MTPs should be the same as that used in isometric trials and measured during the familiarisation session undertaken prior to the testing. After the athlete has been positioned as previously described, two submaximal IMTP warm-up trials should be performed. The first should be performed at 50% of perceived maximum effort, with the second performed at 75% of perceived maximum effort.[10,24,53] These warm-up efforts should be separated by one minute of rest.

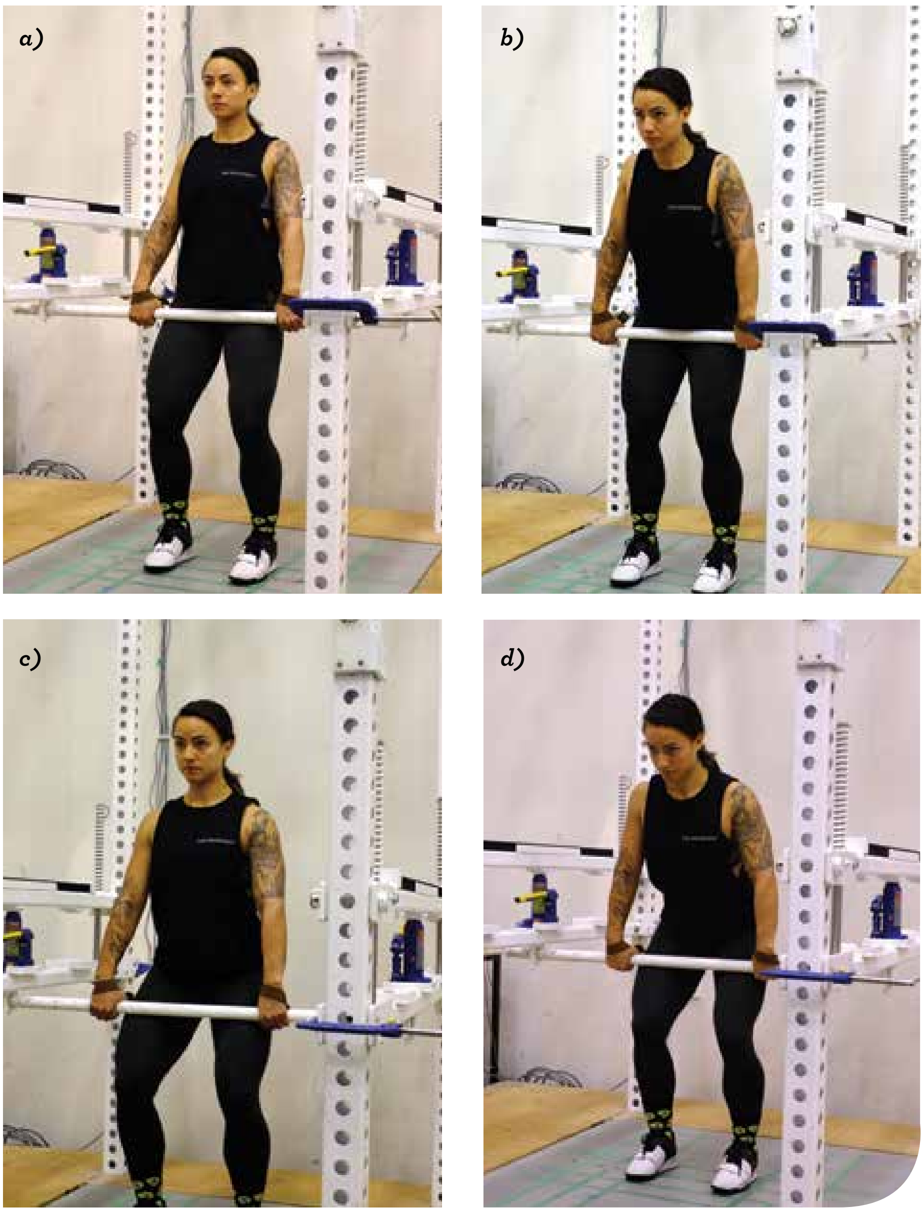
If the athletes undertaking the IMTP are unfamiliar with the weightlifting movements, particularly those performed from the mid-thigh position, or are contraindicated from performing them, it is advised that strength and conditioning professionals proceed directly from the generalised dynamic warm-up to the specific warm-up of submaximal IMTP efforts of increasing perceived intensity.[7,8]

FAMILIARISATION AND TESTING PROCEDURES

Before undertaking testing in the IMTP, athletes should be familiarised with both the mechanics of the test and the procedures to be used. Although there is limited research on the number of familiarisation sessions required to negate the effects of the learning effect upon force output, it appears that a single session containing four submaximal trials is sufficient[4] to optimise force outcomes, which is less than the six to ten submaximal trials required to optimise performance in the ISqT.[18,43] However, there is no available literature on a definable number of sessions required to optimise RFD outcomes, which has been suggested to require substantial familiarisation.[34] Similarly, the amount of familiarisation required to generate reliable IMP characteristics is currently unknown. As such, based on the existing literature, athletes should undertake a minimum of one familiarisation session prior to testing. Furthermore, if RFD or IMP characteristics are used to assess skeletal muscle function, additional familiarisation may be required to result in reliable values.

Prior to commencing the trial, the participants should be attached to the immovable barbell using weightlifting straps or a combination of weightlifting straps and athletic tape,[23] after which

Figure 1. The correct IMTP starting position and common mistakes in the start position (a: The correct IMTP start position; b: correct barbell position with torso incorrectly lent forwards; c: barbell position too low and knees excessively bent; d: barbell position too low, knees excessively bent and torso excessively inclined)



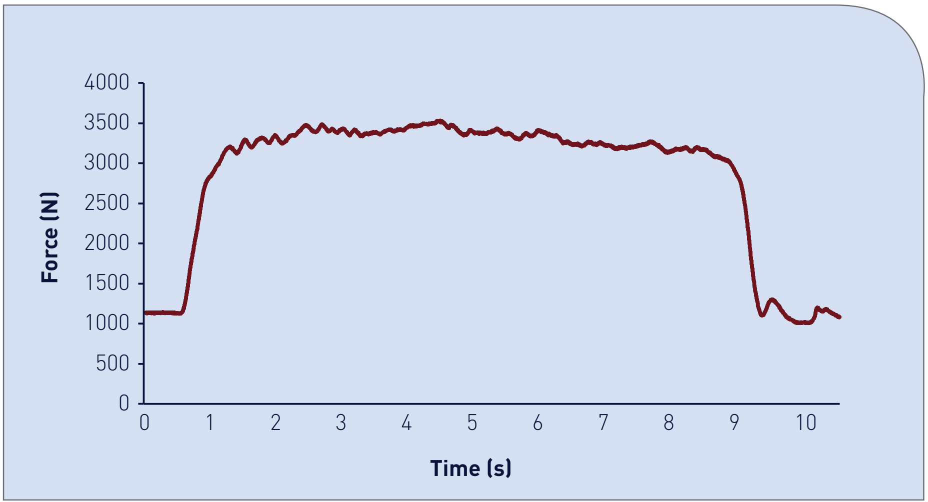


Figure 2. Correctly performed IMTP test with a stable pre-trial force trace

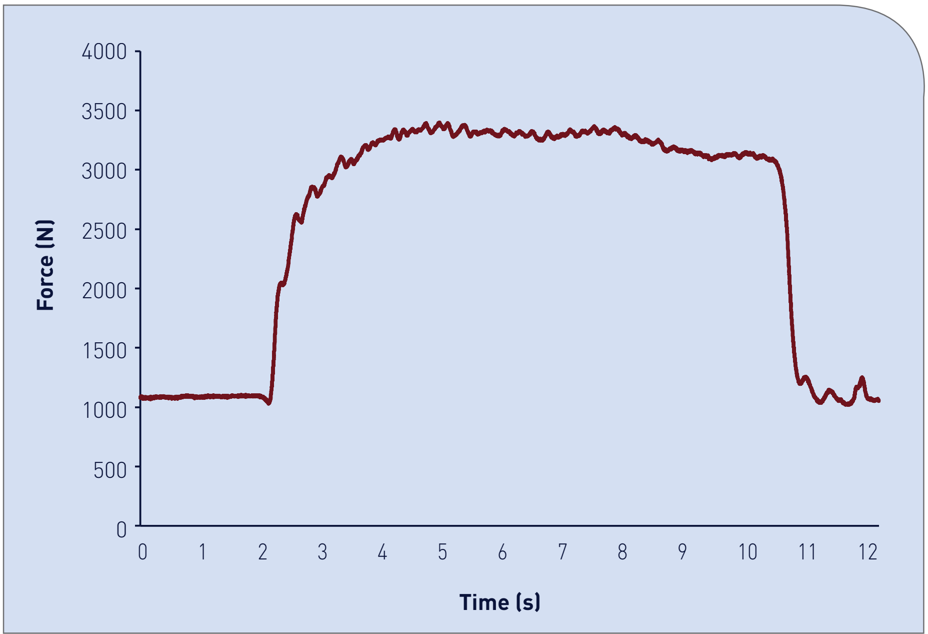


Figure 3. IMTP trial with countermovement prior to initiation

the athlete should apply the minimum amount of pre-tension required to remove slack from the 'system'.[3,23] This stable amount of pre-tension should be established visually via observation of a stable force trace, maintained for a minimum of one second in the desired IMTP position. (See Figure 2).[12] To ensure that only the minimum required pre-tension is applied, a one second weighing period in a relaxed posture should be performed immediately after the termination of the trial with only a 50-100 N tolerance between pre- and post-trial force values. Trials where this stable level of pre-tension is absent or there is a visible countermovement upon trial initiation should be excluded from subsequent analysis (See Figure 3).

Once this stable position has been established, the athlete should be given a countdown of '3, 2, 1, pull', with instructions provided prior to the initiation of experimental trials to 'pull as fast and as hard as possible'.[23,25] Strong verbal encouragement should also be provided throughout the duration of the trial to ensure the athlete is providing maximal effort. Trials should be terminated after a five second window has elapsed or once the force trace visually declines, whichever occurs first. Three to five trials should be performed, with results averaged across the three trials with the greatest PF values.[34] Trials with a greater than 250 N difference to the other trials should be excluded from subsequent analysis.

FORCE TIME CURVE ANALYSIS

Ideally after collection of IMTP trials, there should be minimal filtering applied to the signal, preventing the disruption of the baseline noise level of the signal or the shifting of time within the force signal.[34] This is particularly important should the onset of IMTP trials be determined manually or if other testing modalities are concurrently utilised (EMG etc).[34] However, should filtering be unavoidable due to excessive baseline noise, then a zero lag, low-amplitude digital filter such as a fourth-order Butterworth set at the highest available cut-off frequency should be used so as to minimise potential distortion of time within a trial.[34] If filtering is utilised, practitioners should take into account the potential for underestimation of force-time characteristics when comparing filtered data to unfiltered data.[14]

DETERMINATION OF TRIAL ONSET

There are several methods utilised within the scientific literature to determine the onset of force application during an isometric trial, with either manual identification or an automated detection method being the most common.[9,12] Traditionally, manual/visual identification of the onset of force application has been used in the IMTP[3,6,23] and this method remains the gold standard against which automated onset detection methodologies are typically validated in both isometric and dynamic trials.[55] Recently, however, Dos'Santos et al[12] compared a number of onset thresholds in the analysis of force-time curves produced during the IMTP; they reported that utilising an onset threshold of five times the standard deviation of the mean force recorded during a one-second weighing period prior to trial initiation resulted in the most accurate determination of time-specific force and RFD values when compared to either percentages of body weight (2.5, 5, 10%) or an arbitrary 75 N rise above body weight.[12] Therefore, although the visual identification of force onset is recommended due to its continuing status as the 'gold standard' method for force onset detection during isometric testing,[26,34,54,55] it is

Table 1. Commonly quantified force characteristics during analysis of the force-time curve produced in the IMTP

FORCE CHARACTERISTIC		ABBREVIATION	UNIT OF MEASURE	CALCULATED BY
Peak Force	Absolute peak force	PF	N	PF recorded subtract body mass
	Peak force relative to body mass	PF_{kg}	N/kg	PF divided by body mass
	Peak force allometrically scaled	PF_{a}	$N/kg^{*0.67}$	PF divided by body mass to the power of -0.67
Time Specific Force	Force at 50ms	F_{50}	N	F at 50ms subtract body mass
	Force at 50ms, relative to body mass	F_{kg50}	N/kg	F_{50} divided by body mass
	Force at 50ms, allometrically scaled	F_{a50}	$N/kg^{-0.67}$	F_{50} divided by body mass to the power of -0.67
	Force at 100ms	F_{100}	N	F at 100ms subtract body mass
	Force at 100ms, relative to body mass	F_{kg100}	N/kg	F_{100} divided by body mass
	Force at 100ms, allometrically scaled	F_{a100}	$N/kg^{-0.67}$	F_{100} divided by body mass to the power of -0.67
	Force at 150ms	F_{150}	N	F at 150ms subtract body mass
	Force at 150ms, relative to body mass	F_{kg150}	N/kg	F_{150} divided by body mass
	Force at 150ms, allometrically scaled	F_{a150}	$N/kg^{-0.67}$	F_{150} divided by body mass to the power of -0.67
	Force at 200ms	F_{200}	N	F at 200ms subtract body mass
	Force at 200ms, relative to body mass	F_{kg200}	N/kg	F_{200} divided by body mass
	Force at 200ms, allometrically scaled	F_{a200}	$N/kg^{-0.67}$	F_{200} divided by body mass to the power of -0.67
	Force at 250ms	F_{250}	N	F at 250ms subtract body mass
	Force at 250ms, relative to body mass	F_{kg250}	N/kg	F_{250} divided by body mass
	Force at 20ms, allometrically scaled	Fa_{250}	$N/kg^{-0.67}$	F_{250} divided by body mass to the power of -0.67

Table 2. Commonly quantified rate of force development characteristics during analysis of the force-time curve produced in the IMTP

RATE OF FORCE CHARACTERISTIC		ABBREVIATION	UNIT OF MEASURE	CALCULATED BY
Rate of force develop-ment	Rate of force development	RFD	N/s	Change in force / change in time
	Average rate of force development	avgRFD	N/s	PF / time to PF from force onset
	Peak rate of force development	pRFD	N/s	PF / sampling window
Time specific rate of force develop-ment	Rate of force development 0-50ms	$RFD_{0\text{-}50}$	N/s	F_{50ms} / 50ms
	Rate of force development 0-100ms	$RFD_{0\text{-}100}$	N/s	F_{100ms} / 100ms
	Rate of force development 0-150ms	$RFD_{0\text{-}150}$	N/s	F_{150ms} / 150ms
	Rate of force development 0-200ms	$RFD_{0\text{-}200}$	N/s	F_{200ms} / 200ms
	Rate of force development 0-250ms	$RFD_{0\text{-}250}$	N/s	F_{250ms} / 250ms
	Rate of force development 50-100ms	$RFD5_{0\text{-}100}$	N/s	$(F_{100ms}\text{-}F_{50ms})$ / 50ms
	Rate of force development 100-200ms	$RFD_{100\text{-}200}$	N/s	$(F_{200ms}\text{-}F_{100ms})$ / 100ms
	Rate of force development 200-250ms	$RFD_{200\text{-}250}$	N/s	$(F_{250ms}\text{-}F_{200ms})$ / 50ms

possible for practitioners to utilise either methodology to determine the onset of force application and obtain accurate force-time characteristics in the IMTP. It is, however, important that when visually identifying the onset of force application that the trial used contains no countermovement and a stable force trace prior to trial initiation. The absence of a stable pre-trial force trace or the presence of an observable countermovement prior to trial initiation may result in the incorrect determination of force onset and therefore incorrect calculation of time-dependent force-time characteristics.[34]

FORCE MEASURES

Both peak and time-based measures of force can be determined during analysis of the force-time curves produced in the IMTP.[23,24] The maximum force produced during the five second duration of the trial should be reported as the PF. Furthermore, force produced at 30, 50, 90, 100, 150, 200, and 250 ms meet the two-level reliability criteria (ICCα >0.70, CV <15%) set out by Haff et al[23] and therefore can be used during analysis of the force-time curve. These force-time variables are also commonly expressed relative to the athlete's body mass and/or allometrically scaled to remove

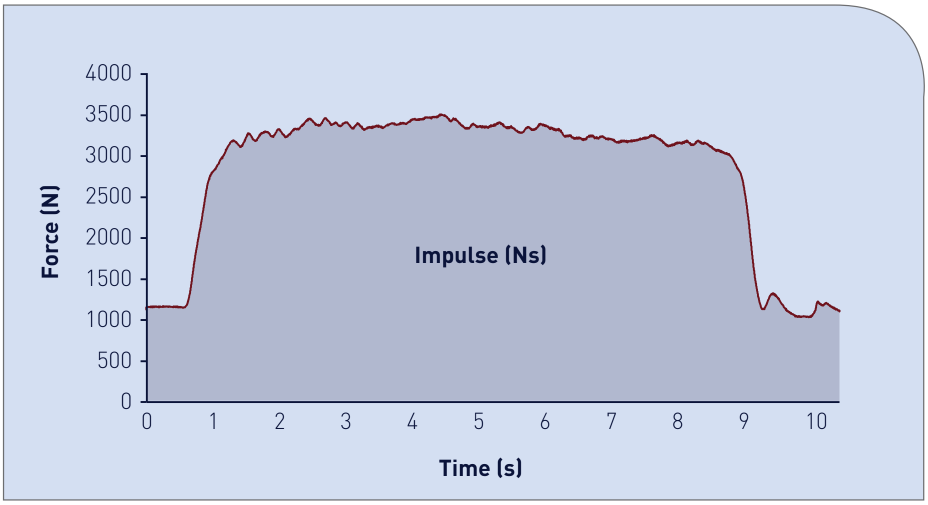


Figure 4. Force-time curve with impulse shaded under the force trace

differences between body sizes.[20,42,59] Equations for the calculation of force variables can be found in Table 1.

RATE OF FORCE DEVELOPMENT

Along with force characteristics, rate of force development (RFD) is commonly determined during analysis of the force-time curve.[23] Although a number of measures such as average RFD (avgRFD), peak RFD (pRFD), time-specific RFD, index of explosiveness, reactivity co-efficient, S-gradient, and A-gradient have been suggested or utilised,[3,29,32,61] not all demonstrate acceptable reliability.[7,23] As such, it is recommended that practitioners ensure that the variable(s) they use to evaluate RFD is/are reliable to ensure adaptations to training or changes in fatigue levels are accurately interpreted. Strength and conditioning professionals should therefore endeavour to use time-specific RFD bands such as 0-30, 0-50, 0-90, 0-100, 0-150, 0-200, and 0-250 ms when analysing force-time curves produced in the IMTP.[23]

Furthermore, while pRFD measured using a 20 ms sampling window meets the reliability criteria set out by Haff et al,[23] the upper values of both the co-efficient of variation and confidence intervals both fail the required standard, making its use as an assessment tool questionable. Similarly, Brady et al[7] reported pRFD is unreliable, regardless of the sampling window used during calculation. Practitioners should therefore be aware of the potential for error between sessions when using pRFD calculated with a 20 ms sampling window as a diagnostic tool. Equations for the calculation of RFD variables can be found in Table 2.

IMPULSE

Although performance markers such as sprinting or change of direction are commonly related to the strength levels displayed or power output expressed during a squat,[35] power clean,[2] or countermovement jump,[11] any significant relationship simply describes the performance outcome, not the underlying mechanisms of performance.[44,60] Impulse, however, has a near-perfect relationship with jumping performance,[44,60] with impulse produced at 100 ms and 300 ms in the IMTP also demonstrating a strong negative relationship to both sprint performance over short distances (5, 20m) and change of direction ability.[51] In the IMTP, isometric impulse is calculated through the multiplication of the average force recorded in a given time period by the length of the time period, i.e. the area underneath the force-time curve (see Figure 4).[7,19,21] Equations for the calculation of impulse can be found in Table 3.

Importantly, although Thomas et al[51] demonstrated strong reliability (ICC = 0.96-0.97, CV = 3.1-3.2%) for impulse at 100 ms and 300 ms, subsequent research by Thomas et al[52] has found small, significant differences (p =0.032-0.045) in inter-day measures of impulse at 100, 200, and 250 ms despite acceptable ICC (0.76-0.81) and CV (9.11-9.29%) values.[51,52] Brady et al[7] also reported that impulse in pre-determined time bands of 0-100 ms, 0-200 ms and 0-250 ms are an unreliable measure in the IMTP. Practitioners should therefore use caution when using impulse to monitor skeletal muscle function via the IMTP, as it is not clear from the available scientific literature that it is a reliable measure.

Conclusions

The IMTP is a reliable and efficient measure of an athlete's maximum force-generating capacity and rate that he/she develops force; however, the position used during testing has a significant impact upon the magnitude of the force-time characteristics displayed. Furthermore, the methods of analysing force-time characteristics can have a significant effect upon the magnitude and reliability of measures and therefore the ability to accurately assess skeletal muscle function. Specific recommendations, including suggested barbell position and body posture, for the performance of the IMTP can be found in Table 4.

Table 3. Commonly quantified impulse characteristics during analysis of the force-time curve produced in the IMTP

IMPULSE CHARACTERISTIC		ABBREVIATION	UNIT OF MEASURE	CALCULATED BY
IMPULSE	TOTAL IMPULSE	IMP	N/S	AVERAGE FORCE X TIME
Time Specific Impulse	Impulse 0-100ms	IMP_{100ms}	Ns	$\sum F_{0\text{-}100ms}$ x 100ms
	Impulse 0-200ms	IMP_{200ms}	Ns	$\sum F_{0\text{-}200ms}$ x 200ms
	Impulse 0-300ms	IMP_{300ms}	Ns	$\sum F_{0\text{-}300ms}$ x 300ms

Table 4. Recommendations

FACTOR	RECOMMENDATION
Warm-up	Prior to testing a ~5-minute dynamic warm up should be performed. Following this, 3 sets of dynamic mid-thigh pulls for 3-5 reps of increasing submaximal intensity (40, 60, 80% 1RM power clean) should be performed. Following this, 2 IMTPs of increasing submaximal intensity (50, 75%) should be performed. If a 1RM power clean is not established, an estimated or perceived maximum can be used. If athletes are unfamiliar with weightlifting movements or are contraindicated from performing them, they should proceed straight from the general dynamic warm-up to the submaximal warm-up IMTPs
Barbell position	The barbell position should match the position found at the initiation of the second pull of the clean
Hip- and knee-angle	Hip- and knee-angles will depend upon individual anthropometrics – however, typically will fall within the range of 140-145° and 130-145° respectively. These should be measured and recorded for each athlete and then maintained throughout each testing session
Grip and foot position	Both grip and foot position should be measured/recorded during dynamic performance of the clean and used throughout all IMTP testing
Equipment requirements	A force plate with a sampling rate of 1000Hz should be preferentially used to avoid signal aliasing and should be positioned below either a custom or portable IMTP rig that allows no movement of the barbell. The barbell should also be able to be adjusted to any height above the force plate
Filtering of data	Data should preferably be left unfiltered, however, if filtering is unavoidable due to excessive signal noise: a low pass filter such as a 4th order Butterworth should be used
Analysis of force characteristics	Both peak and time-specific force values are a reliable measure of force-generating capacity
Analysis of rate of force development	Average and peak values of rate of force development are unreliable and should be avoided. Rate of force development during specific time-bands is a reliable measure; however, it is unclear whether very short time-bands (0-30, 0-50, 0-90 ms) are reliable and they should be used with caution.

AUTHORS' BIOGRAPHIES

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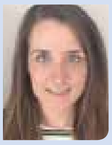

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References

1. Bailey CA, Sato K, Burnett A, and Stone MH. Force-production asymmetry in male and female athletes of differing strength levels. *International Journal of Sports Physiology and Performance* 10, 2015.
2. Baker D and Nance S. The relation between running speed and measures of strength and power in professional rugby league players. *Journal of Strength & Conditioning Research* 13: 230-235, 1999.
3. Beckham G, Mizuguchi S, Carter C, Sato K, Ramsey M, Lamont H, Hornsby G, Haff G, and Stone M. Relationships of isometric mid-thigh pull variables to weightlifting performance. *Journal of Sports Medicine and Physical Fitness* 53: 573-581, 2013.
4. Beckham GK. The effect of various body positions on performance of the isometric mid-thigh pull, in: *Department of Exercise and Sport Sciences*. East Tennessee State University, 2015, p 92.
5. Beckham GK, Lamont HS, Sato K, Ramsey MW, Haff GG, and Stone MH. Isometric strength of powerlifters in key positions of the conventional deadlift. *Journal of Trainology* 1: 32-35, 2012.
6. Beckham GK, Sato K, Mizuguchi S, Haff GG, and Stone MH. Effect of body position on force production during the isometric mid-thigh pull. *Journal of Strength & Conditioning Research* 32: 48-56, 2018.
7. Brady CJ, Harrison AJ, Flanagan EP, Haff GG, and

References

Comyns TM. A comparison of the isometric mid-thigh pull and isometric squat: Intraday reliability, usefulness, and the magnitude of difference between tests. *International Journal of Sports Physiology and Performance* 13: 844-852, 2018.

8. Brownlee TE, Murtagh CF, Naughton RJ, Whitworth-Turner CM, O'Boyle A, Morgans R, Morton JP, Erskine RM, and Drust B. Isometric maximal volutary force evaluated using an isometric mid-thigh pull differentiates English Premier League youth soccer players from a maturity-matched control group. *Science and Medicine in Football* 2: 209-215, 2018.
9. Carroll KM, Wangle JP, Sato K, DeWeese BH, Mizuguchi S, and Stone MH. Reliability of a commercially avaliable and algorithm based kinetic analysis software compared to manual-based software. *Sports Biomechanics* In Press, 2017.
10. Comfort P, Jones PA, McMahon JJ, and Newton RU. Effect of knee and trunk angle on kinetic variables during the isometric midthigh pull: Test-retest reliability. *International Journal of Sports Physiology and Performance* 10: 58-63, 2015.
11. Conlon J, Haff GG, Nimphius S, Tran T, and Newton RU. Vertical jump velocity as a determinant of speed and agility performance. *Journal of Australian Strength & Conditioning* 21: 88-90, 2013.
12. Dos'Santos T, Jones PA, Comfort P, and Thomas C. Effect of different onset thresholds on isometric mid-thigh pull force-time variables. *Journal of Strength & Conditioning Research* 31: 3463-3473, 2017.
13. Dos'Santos T, Jones PA, Kelly J, McMahon JJ, Comfort P, and Thomas C. Effect of sampling frequency on isometric midthigh-pull kinetics. *International Journal of Sports Physiology and Performance* 11: 255-260, 2016.
14. Dos'Santos T, Lake J, Jones PA, and Comfort P. Effect of low-pass filtering on isometric mid-thigh pull kinetics. *Journal of Strength & Conditioning Research* 32: 983-989, 2018.
15. Dos'Santos T, Thomas C, Comfort P, McMahon JJ, Jones PA, Oakley NP, and Young AL. Between-session reliability of isometric mid-thigh pull kinetics and maximal power clean performance in male youth soccer players. *Journal of Strength & Conditioning Research* 32: 3364-3372, 2018.
16. Dos'Santos T, Thomas C, Jones PA, McMahon JJ, and Comfort P. The effect of hip joint angle on isometric mid-thigh pull kinetics. *Journal of Strength & Conditioning Research* 31: 2748-2757, 2017.
17. Dos'Santos T, Thomas C, Comfort P, McMahon JJ, and Jones PA. Relationships between isometric force-time characteristics and dynamic performance. *Sports* 5: 68-80, 2017.
18. Drake D, Kennedy R, and Wallace E. Familiarization, validity and smallest detectable difference of the isometric squat testing evaluating maximal strength. *Journal of Sports Sciences* 36: 2087-2095, 2018.
19. Enoka R. Impulse, in: Neuromechanics of human movement. L Robertson, M Eckstein, C Cohen, J Sexton, eds. Champaign, IL: *Human Kinetics*, 2008, pp 68-71.
20. Folland JP, McCauley TM, and Williams AG. Allometric scaling of strength measurements to body size. *European Journal of Applied Physiology* 102: 739-745, 2008.
21. Grimshaw P, Fowler N, Lees A, and Burden A. *Instant Notes in Sport and Exercise Biomechanics*. Abingdon, Oxon: Taylor & Francis, 2005.
22. Haff GG, Carlock JM, Hartman MJ, Kilgore JL, Kawamori N, Jackson JR, Morris RT, Sands WA, and Stone MH. Force-time curve characteristics of dynamic and isometric muscle actions of elite women olympic weightlifters. *Journal of Strength & Conditioning Research* 19: 741-748, 2005.
23. Haff GG, Ruben RP, Lider J, Twine C, and Cormie P. A comparison of methods for determining the rate of force development during isometric midthigh clean pulls. *Journal of Strength & Conditioning Research* 29: 386-395, 2015.
24. Haff GG, Stone M, O'Bryant HS, Harman E, Dinan C, Johnson R, and Han K-H. Force-time dependent characteristics of dynamic and isometric muscle actions. *Journal of Strength & Conditioning Research* 11: 269-272, 1997.
25. Halperin I, Williams K, Martin DT, and Chapman DW. The effects of attentional focusing instructions on force production during the isometric mid-thigh pull. *Journal of Strength & Conditioning Research* 30: 919-923, 2016.
26. Hannah R, Minshull C, Buckthorpe MW, and Folland JP. Explosive neuromuscular performance of males versus females. *Experimental Physiology* 97: 618-629, 2012.
27. Hornsby WG, Gentles JA, MacDonald CJ, Mizuguchi S, Ramsey MW, and Stone MH. Maximum strength, rate of force development, jump height, and peak power alterations in weightlifters across five months of training. *Sports* 5: 78, 2017.
28. Hornsby WG, Haff GG, Sands WA, Ramsey MW, Beckham GK, Stone ME, and Stone MH. Alterations in strength characteristics for isometric and dynamic mid-thigh pulls in collegiate throwers across 11 weeks of training. *Gazzetta Medica Italiana* 172: 929-940, 2013.
29. Kawamori N, Rossi SJ, Justice BD, Haff EE, Pistilli EE, O'Bryant HS, Stone MH, and Haff GG. Peak force and rate of force development during isometric and dynamic mid-thigh clean pulls performed at various intensities. *Journal of Strength & Conditioning Research* 20: 483-491, 2006.
30. Konrad P. The ABC of EMG: A practical introduction of kinesiological electromyography. Scottsdale, AX: Noraxon INC, 2005.
31. Kraska JM, Ramsey MW, Haff GG, Fethke N, Sands WA, Stone ME, and Stone MH. Relationship between strength characteristics and unweighted and weighted vertcal jump height. International *Journal of Sports Physiology and Performance* 4: 461-473, 2009.
32. Leary BK, Statler J, Hopkins B, Fitzwater R, Kesling T, Lyon J, Phillips B, Bryner RW, Cormie P, and Haff GG. The relationship between isometric force-time curve characteristics and club head speed in recreational golfers. *Journal of Strength and Conditioning Research* 26: 2685-2697, 2012.
33. Luce GD. Fundamental concepts in EMG signal acquisition. Natick, Massachusetts: DelSys Inc, 2003.
34. Maffiuletti NA, Aagaard P, Blazevich AJ, Folland J, Tillin N, and Duchateau J. Rate of force development: physiological and methodological considerations. *European Journal of Applied Physiology* 116: 1091-1116, 2016.
35. McBride JM, Blow D, Kirby TJ, Haines TL, Dayne AM, and Triplett NT. Relationship between maximal squat strength and five, ten, and forty yard sprint times. *Journal of Strength & Conditioning Research* 23: 1633-1638, 2009.
36. McGuigan MR, Newton MJ, and Winchester JB. Use of isometric testing in soccer players. *Journal of Australian Strength & Conditioning* 16: 11-14, 2008.
37. McGuigan MR, Newton MJ, Winchester JB, and Nelson AG. Relationship between isometric and dynamic strength in recreationally trained men. *Journal of Strength & Conditioning Research* 24: 2570-2573, 2010.
38. McGuigan MR and Winchester JB. The relationship between isometric and dynamic strength in college football players. *Journal of Sports Science and Medicine* 7: 101-105, 2008.
39. McGuigan MR, Winchester JB, and Erickson T. The importance of isometric maximum strength in college wrestlers. *Journal of Sports Science and Medicine* 5: 108-113, 2006.
40. McMaster DT, Gill N, Cronin J, and McGuigan M. A brief review of strength and ballistic assessment methodologies in sport. *Sports Medicine* 44: 603-623, 2014.
41. Nyquist H. Certain topics in telegraph transmission theory. *Transactions of the AIEE* 47: 617-644, 1928.
42. Painter KB, Haff GG, Ramsey MW, McBride J, Triplett T, Sands WA, Lamont HS, Stone ME, and Stone MS. Strength Gains: Block vs daily undulating periodization weight-training among track and field athletes. *International Journal of Sports Physiology and Performance* 7: 161-169, 2012.
43. Pekunlu E and Ozsu I. Avoiding systematic errors in isometric squat-related studies without pre-familiarisation by using sufficent numbers of trials. *Journal of Human Kinetics* 42: 201-213, 2014.

References

44. Ruddock AD and Winter EM. Jumping depends on impulse not power. *Journal of Sports Sciences* 34: 584-585, 2016.
45. Sahaly R, Vandewalle H, Driss T, and Monod H. Maximal voluntary force and rate of force development in humans - importance of instruction. *European Journal of Applied Physiology* 85: 345-350, 2001.
46. Secomb JL, Jundgren LE, Farley ORL, tran TT, Nimphius S, and Sheppard JM. Relationship between lower-body muscle structure and lower-body strength, power, and muscle-tendon complex stiffness. *Journal of Strength & Conditioning Research* 29: 2221-2228, 2015.
47. Secomb JL, Nimphius S, Farley ORL, Lundgren LE, Tran TT, and Sheppard JM. Relationship between lower-body muscle structure and, lower-body strength, explosiveness and eccentric leg stiffness in adolescent athletes. *Journal of Sports Science and Medicine* 14, 2015.
48. Stone MH, O'Bryant HS, McCoy L, Coglianese R, Lehmkuhl M, and Schilling B. Power and maximum strength relationships during performance of dynamic and static weighted jumps. *Journal of Strength & Conditioning Research* 17: 140-147, 2003.
49. Stone MH, Sanborn K, O'Bryant HS, Hartman M, Stone ME, Proulx C, Ward B, and Hruby J. Maximum strength-power-performance relationships in collegiate throwers. *Journal of Strength & Conditioning Research* 17: 739-745, 2003.
50. Stone MH, Sands WA, Carlock J, Callan S, Dickie D, Daigle K, Cotton J, Smith SL, and Hartman M. The importance of isometric maximum strength and peak rate of force development in sprint cycling. *Journal of Strength & Conditioning Research* 18: 878-884, 2004.
51. Thomas C, Comfort P, Chiang C-Y, and Jones PA. Relationship between isometric mid-thigh pull variables and sprint and change of direction performance in collegiate athletes. *Journal of Trainology* 4: 6-10, 2015.
52. Thomas C, Dos'Santos T, Comfort P, and Jones PA. Between-session reliability of common strength- and power-related measures in adolescent athletes. *Sports* 5: 1-11, 2017.
53. Thomas C, Jones PA, Rothwell J, Chiang CY, and Comfort P. An investigation into the relationship between maximum isometric strength and vertical jump performance. *Journal of Strength & Conditioning Research* 29: 2176-2185, 2015.
54. Tillin NA, Jimenez-Reyes P, Pain MTG, and Folland JP. Neuromuscular performance of explosive power athletes versus untrained individuals. *Medicine & Science in Sports & Exercise* 42: 781-790, 2010.
55. Tillin NA, Pain MTG, and Folland J. Identification of contraction onset during explosive contractions. Response to Thompson et al. "Consistency of rapid muscle force characteristics: Influence of muscle contraction onset detection mehtodology [J Electromyogr Kinesiol 2012; 22(6): 893-900]. *Journal of Electromyography and Kinesiology* 23: 991-994, 2013.
56. Tran TT, Lundgren L, Secomb J, Farley ORL, Haff GG, Nimphius S, Newton RU, Brown LE, and Sheppard JM. Effect of four weeks detraining on strength, power, and sensorimotor ability of adolescent surfers. *The Open Sports Science Journal* 10: 71-80, 2017.
57. Tran TT, Lundgren L, Secomb J, Farley ORL, Haff GG, Seitz LB, Newton RU, Nimphius S, and Sheppard JM. Comparison of physical capacities between nonselected and selected elite male competitive surfers for the National Junior Team. International *Journal of Sports Physiology and Performance* 10: 178-182, 2015.
58. Wang R, Hoffman JR, Tanigawa S, Miramonti AA, Monica MBL, Beyer KS, Church DD, Fukuda DH, and Stout JR. Isometric mid-thigh pull correlates with strength, sprint, and agility performance in collegiate rugby union players. *Journal of Strength & Conditioning Research* 30: 3051-3056, 2016.
59. West DJ, Owen NJ, Jones MR, Bracken RM, Cook CJ, Cunningham DJ, Shearer DA, Finn CV, Newton RU, Crewther BT, and Kilduff LP. Relationships between force-time characteristics of the isometric midthigh pull and dynamic performance in professional rugby league players. *Journal of Strength & Conditioning Research* 25: 3070-3075, 2011.
60. Winter EM. Jumping: Power or Muscle. *Medicine & Science in Sports & Exercise* 37: 523, 2005.
61. Zatsiorsky VM and Kramer WJ. *Science and Practice of Strength Training*. Champaign, IL: Human Kinetics, 2006.