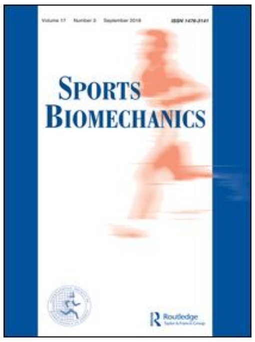

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A comparison of manual and automatic force-onset identification methodologies and their effect on force-time characteristics in the isometric midthigh pull

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ABSTRACT
The aim of this study was to assess the agreement of three different automated methods of identifying force-onset (40 N, 5 SDs, and 3 SDs) with manual identification, during the isometric mid-thigh pull (IMTP). Fourteen resistance-trained participants with >6 months experience training with the power clean volunteered to take part. After three familiarisation sessions, the participants performed five maximal IMTPs separated by 1 min of rest. Fixed bias was found between 40 N and manual identification for time at force-onset. No proportional bias was present between manual identification and any automated threshold. Fixed bias between manual identification and automated was present for force at onset and F_{150}. Proportional but not fixed bias was found for F_{50} between manual identification and all automated thresholds. Small to moderate differences (Hedges g = −0.487- −0.692) were found for F_{90} between all automated thresholds and manual identification, while trivial to small differences (Hedges g = −0.122—−0.279) were found between methods for F_{200} and F_{250}. Based on these results, strength and conditioning practitioners should not use a 40 N, 5 SDs, or 3 SDs threshold interchangeably with manual identification of force-onset when analysing IMTP force–time curve data.

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Performance testing; maximum strength; strength testing

Introduction

Isometric tests, such as the isometric mid-thigh pull (IMTP), allow for the accurate and time-efficient assessment of force-generating capacity in both athletic and non-athletic populations. Due to the ability to create force–time curves from data collected during isometric tests, it is possible to assess multiple components of an athlete's force-generating capacity within a single test (Brady et al., 2020a; Maffiuletti et al., 2016). These components include maximal force-generating capacity, rate of force development (RFD), and impulse (IMP), which are each commonly thought to underpin sports

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performance (Brady et al., 2020b; Haff et al., 2015, 1997; Thomas et al., 2015). Furthermore, owing to the mechanical simplicity inherent to multi-joint isometric tests, they may be more time-efficient and less fatiguing than the performance of dynamic multi-joint tests (Stone et al., 2019). When utilised concurrently with traditional dynamic tests of maximum strength, multi-joint isometric tests may also enable a more complete assessment of neuromuscular adaptations resulting from imposed training stimuli (Buckner et al., 2017).

Force-time characteristics of the IMTP display relationships of differing strength to common markers of athletic performance and dynamic measures of strength. For example, peak force (PF) in the IMTP displays the strongest relationship to one repetition maximum squat and deadlift (McGuigan et al., 2010; McGuigan & Winchester, 2008; Witt et al., 2018). Furthermore, both PF and time-dependent force characteristics display moderate to moderately strong relationships with short sprinting time (10–20 m), vertical jump height, and 5-0-5 change of direction time (Kraska et al., 2009; Nuzzo et al., 2008; Thomas et al., 2015; West et al., 2011), particularly when calculated relative to body mass. However, while PF and time-dependent forces in the IMTP are highly reliable (Brady et al., 2020a; Comfort et al., 2020; Haff et al., 2015), the testing and analysis protocols used within the literature during the IMTP are varied, which likely compromises the ultimate comparability of the results contained within the literature (Comfort et al., 2019; Guppy et al., 2018). Of particular note is the many different methods of identifying force-onset.

During isometric testing, traditionally force-onset has been identified manually, and is considered by some to be the gold-standard methodology for analysing isometric force–time curve data (Maffiuletti et al., 2016; Tillin et al., 2013). During the analysis of IMTP force–time curve data a variety of methods have been reported in the literature, with Beckham et al. (2018), Guppy et al. (2019), and Moeskops et al. (2018) all employing a manual identification of the force-onset, while Brady et al. (2018), Dos'Santos et al. (2017b), and Keogh et al. (2020) identified force-onset as '*the point at which force exceeded 5 SDs from baseline*'. Dos'Santos et al. (2017a) reported that an onset threshold of 5 SDs BW better accounts for the signal noise inherent in the 1 s pre-trial weighing period (i.e., the baseline) than the threshold of an absolute rise in force of 75 N, and therefore results in lower time-dependent force and RFD characteristics, which are less likely to be overestimations of force-generating capacity. Similarly, Chavda et al. (2020) also suggested using a 5 SDs threshold relative to the baseline noise to identify force-onset. It has been suggested that using automated thresholds may improve workflow efficiency when analysing IMTP trials compared with manual identification (Chavda et al., 2020).

To date however, only one study investigating the IMTP has directly compared the accuracy of automated relative thresholds, such as those recommended by Chavda et al. (2020) and Dos'Santos et al. (2017a), with manual identification of force-onset (Pickett et al., 2019). Pickett et al. (2019) reported data from two IMTP trials that suggested automated thresholds of 1 SD BW, 2 SDs BW, 3 SDs BW, 5 SDs BW, and a 40 N absolute rise in vertical force above baseline resulted in delayed identification of force-onset when compared with manual identification. However, trials that contained a visually obvious countermovement upon force application or an unstable baseline prior to the initiation of the trial were included in the study's analysis (Pickett et al., 2019), which contradicts the general recommendations for the performance and analysis of isometric trials (Maffiuletti et al., 2016; Rodriguez-Rosell et al., 2018) and also established practice for analysing IMTP force–time curves (Brady et al., 2020a, 2018; Chavda et al., 2020; Comfort et al., 2019; Dos'Santos et al., 2017a; Guppy et al., 2018, 2019; Haff et al., 2015). Furthermore, it is important to note that no familiarisation was provided to the participants prior to IMTP testing (Pickett et al., 2019). In conjunction with the retention of trials with an unstable baseline and/or a visually obvious countermovement for analysis (Pickett et al., 2019), it is likely that the validity of the automated thresholds was reduced given that a stable baseline period is a prerequisite for their use (Chavda et al., 2020; Comfort et al., 2019; Dos'Santos et al., 2017a; Maffiuletti et al., 2016). Specifically, including trials for analysis with an unstable baseline during the 'weighing' period will inflate the SD of the baseline force (Dotan et al., 2016), and therefore delay the identification of force-onset if using the relative threshold method outlined by Dos'Santos et al. (2017a) and Chavda et al. (2020). As such, while the limited data reported by Pickett et al. (2019) does support their contention that automated thresholds may delay the identification of force-onset in comparison to the manual identification method recommended by Tillin et al. (2013), the methodological issues outlined necessitate further investigation of the topic.

Therefore, the aim of this study was to determine whether automated thresholds based on the 'signal noise' during a 1 s quiet standing period prior to the initiation of the trial could be used interchangeably with manual identification of force-onset during the analysis of IMTP trials. We also aimed to assess the reliability of the time-dependent force values calculated using manual identification of force-onset and automated thresholds. Based on previously published literature investigating this topic during analysis of IMTP trials using purely automated thresholds (Dos'Santos et al., 2017a), electromyography (Tenan et al., 2017), single-leg knee extensions (Dotan et al., 2016), and the recommendations of both (Maffiuletti et al., 2016) and Tillin et al. (2013), we hypothesised that automated thresholds would not agree with manual identification.

Methods

Experimental approach

A within-participant, cross-sectional design was used to investigate the agreement between automated and manual methods of identifying force-onset during the analysis of IMTP trials. Participants were asked to attend the laboratory on four occasions, with sessions one to three serving to familiarise themselves with the IMTP protocol and allow for the recording of anthropometric data (height, body mass). Bar height, foot position, and grip width were also recorded and maintained throughout all subsequent trials. These sessions were separated by a minimum of 24 hours. During session four, the participants performed a series of maximal IMTP trials. The data from this session were used for the assessment of agreement between the force-onset identification methods.

Participants

Fourteen resistance trained participants (n = 13 males, 1 female; height = 178.1 ± 10.1 cm; body mass = 90.0 ± 14.1 kg; age = 26.8 ± 4.8 years) from local weightlifting clubs and strength and conditioning facilities volunteered to take part in this study. All participants had greater than 6 months of experience in the power clean and regularly incorporated it and its associated derivatives into their normal resistance training programmes. Participants were instructed not to perform resistance exercise for 48 hours prior to testing. All participants read and returned signed informed consent forms prior to participation in the study, as approved by the Edith Cowan University Human Research Ethics Committee (Project Code: 18434).

Procedures

Prior to commencing the maximal IMTP testing, participants performed a warm-up of dynamic mid-thigh pulls (MTP) (1 set of 3 repetitions) at 40, 60, and 80% of their pre-established or estimated 1RM power clean (Comfort et al., 2019). Once the dynamic MTPs were completed, the participants performed 3 s IMTPs at 50, 75 and 90% of their perceived maximal effort (Brady et al., 2018). Upon completion of the warm-up, the participants were placed in a position matching the second pull of the clean (Comfort et al., 2019; Guppy et al., 2018), with mean hip- and knee-angles of 145.8 ± 4.6° and 144.9 ± 4.6°, respectively. During all trials, the participants were fixed to the barbell using weightlifting straps to standardise grip strength and prevent their hands from slipping during force application (Comfort et al., 2019; Kraska et al., 2009). Joint angles, grip position, and foot position were recorded and maintained throughout all trials. All trials were performed in a custom-designed IMTP rack (Fitness Technology, Adelaide, Australia) that allowed for a cold-rolled steel bar to be placed at any height through a combination of pins and hydraulic jacks, while standing on a force plate (BP12001200, AMTI, Watertown, MA, USA). Once adjusted to the correct height, the bar was further secured through the use of clamps to minimise the compliance of the system (Maffiuletti et al., 2016). Vertical ground reaction forces were collected at 2000 Hz via a BNC-2090 interface box with an analog-to-digital card (NI-6014, National Instruments, TX, USA).

Once positioned correctly, the participants were instructed to '*pull as hard and as fast as you can while pushing your feet into the ground*' (Halperin et al., 2016). Trials were commenced after a countdown of '*3, 2, 1, Pull*', with the participants applying maximum effort for 5 s or until the force-trace visually declined, whichever occurred first. Strong verbal encouragement was provided throughout the trial to ensure maximal effort was applied. In total, each subject completed five maximal IMTP trials, each separated by 1 min of rest (Kraska et al., 2009). If there was a difference in PF of greater than 250 N between trials (Kraska et al., 2009) or excessive pretension (>100 N above BW; mean = 51.0 ± 33.8 N) was present during the second immediately prior to the initiation of a trial (Guppy et al., 2018) that trial was excluded, and an additional trial was performed. The presence of a countermovement upon force application was assessed using a two-stage process. First, trials were visually screened in real-time during data collection, excluded if the investigator deemed a countermovement present, and an additional trial performed (Brady et al., 2020a; Comfort et al., 2019; Guppy et al., 2018). Then, during offline analysis, collected trials were excluded if there was a decrease in force of greater than BW-5 SDs (Chavda et al., 2020).

Isometric force–time curve analysis

All unfiltered force–time curves were analysed using both custom LabVIEW software (Version 14.0, National Instruments) (Guppy et al., 2019; Haff et al., 2015; Moeskops et al., 2018) and a custom Excel spreadsheet (Microsoft, Redmond, WA, USA) (Brady et al., 2018; Chavda et al., 2020; Dos'Santos et al., 2017a). The maximum force generated during the IMTP was reported as the PF. Additionally, force at 50 (F_{50}), 90 (F_{90}), 150 (F_{150}), 200 (F_{200}), and 250 (F_{250}) ms from the initiation of the pull was also calculated. All force-time characteristics calculated in the present study were chosen due to their reported relationships with sprint acceleration (Brady et al., 2020b; Scanlan et al., 2020; Townsend et al., 2019; West et al., 2011), change of direction (Thomas et al., 2015; Townsend et al., 2019), and weightlifting performance (Beckham et al., 2013). Body weight of the participants was included in the calculation of force at onset, PF, and all time-dependent force characteristics (Beckham et al., 2013). The trial with the highest PF when force-onset was identified manually was used for analysis of agreement, while within-session reliability was determined using the two trials with the highest PF.

Identification of force-onset

Force-onset during all trials was identified using four methods: one manual and three automated. The automated identification of force-onset was performed using the methodology outlined by Dos'Santos et al. (2017a) and Chavda et al. (2020), where the force-onset was defined as the point at which force exceeded 3 and 5 SDs, respectively, of the average force calculated during a 1 s weighing period immediately prior to the initiation of the IMTP. Given that a custom-built, fixed IMTP system was used during the testing protocol, it was possible to utilise a lower threshold relative to the 'noise' during the 1 s weight period than 5 SDs of bodyweight to identify the moment of force-onset (Chavda et al., 2020). Force-onset was also identified as the point at which the vertical ground reaction force rose 40 N above the average force calculated during the 1 s weighing period (Comfort et al., 2015).

The manual identification of force-onset was performed in custom LabView software by a single experienced investigator according to the procedures outlined by Tillin et al. (2010) and as performed previously in the literature investigating the IMTP (Beckham et al., 2018; Carroll et al., 2019; Guppy et al., 2019; Haff et al., 2015, 1997). During this analysis procedure, the moment of force-onset was defined as '*the last peak/trough before the signal deflects away from baseline noise*' (Tillin et al., 2010). Briefly, the analysis commenced through the investigator approximating the initiation and end of the trial using movable sliders. Then, a magnified view of the selected portion of the force-trace was visually inspected in a second window and the investigator was able to manually identify the moment of force-onset using arrow keys built into the custom analysis software (Tillin et al., 2010). The intra-rater reliability of this approach was assessed by having the same investigator analyse a sub-sample of five participant's trials on two occasions separated by seven days, and record the time at force-onset. To calculate the inter-rater reliability, two experienced investigators each analysed another subsample of five participant's trials and recorded the time at force-onset.

Statistical analyses

Ordinary least products (OLP) regression analyses were performed to assess the agreement between manual identification and each of the automated threshold methods (Ludbrook, 2002). Significant fixed bias was deemed to be present if the 95% confidence interval (CI) of the intercept did not include zero, while significant proportional bias was considered present if the 95% CI of the slope did not include one (Ludbrook, 2012). The presence of either form of bias indicates that the two methods should not be used interchangeably (Ludbrook, 2012). 95% limits of agreement and Hedge's *g* effect sizes were calculated to estimate the practical difference between the methods (Hedges & Olkin, 1985). ESs were interpreted as trivial ($g < 0.2$), small ($g = 0.2–0.49$), moderate ($g = 0.5–0.79$), and large ($g \geq 0.8$) (Cohen, 1988). Statistical analyses were performed using the R programming language (version 4.0.2) (R Core Team, 2020). The OLP regression analyses were performed according to the procedures outlined by Ludbrook (2012), with bias corrected and accelerated 95% CIs calculated from 10,000 bootstrap resamples (Canty & Ripley, 2020; Davidson & Hinkley, 1997). 95% limits of agreement were calculated according to the procedures of Bland and Altman (1986). Hedge's *g* effect sizes were calculated in a custom script (Hedges & Olkin, 1985), with bias corrected and accelerated 95% CIs for the effect sizes calculated via bootstrap resampling (Canty & Ripley, 2020; Davidson & Hinkley, 1997). Reliability of the force-time characteristics calculated using each identification method was determined by calculating the intraclass correlation (ICC; type 3,1), coefficient of variation (CV), and 95% confidence intervals (CI) in a freely available Excel spreadsheet (Hopkins, 2015). The ICCs of <0.5 were considered to be indicative of poor reliability, 0.5–0.75 of moderate reliability, >0.75–0.9 of good reliability and >0.9 of excellent reliability (Koo & Li, 2016). The magnitude of the CVs were considered good (<5%), moderate (5–10%), or poor (>10%) (Duthie et al., 2003). Both the intra-rater (type 3,1) and inter-rater reliability (type 2,1) were also assessed using the lower-bound 95% CI for the ICC (Koo & Li, 2016) in the same Excel spreadsheet (Hopkins, 2015).

Results

Fixed bias was only found between 40 N and manual identification of force-onset (Figure 2). No proportional bias was found between any of the automated thresholds and manual identification (Table 1). Fixed but not proportional bias was found between all automated thresholds and manual identification of force at onset. Proportional but not fixed bias was found between all automated thresholds and manual identification for F_{50}, while fixed bias was found between 40 N and 5 SDs (Figure 3). Fixed bias was found between all automated thresholds and manual identification for F_{150}, while no fixed or proportional bias was found between automated thresholds and manual identification for F_{90}, F_{200}, and F_{250}. Trivial and small differences were found between manual identification and automated thresholds for onset time and force at onset, respectively. Moderate to large differences were found between manual identification and all automated methods for F_{50} and F_{90} (Table 1), with the magnitude of the difference corresponding to the magnitude of the automated onset threshold. Trivial to small effect sizes were found between manual identification and all automated thresholds during later force epochs (F_{200}, F_{250}). The intra-rater reliability of manual identification was excellent (ICC = 1.00 [0.99, 1.00], with a mean difference of 6 ms (−11, 21) between analysis sessions.

Discussion and implications

The primary finding of this study was that the automated relative thresholds of 3 SDs and 5 SDs agree with the manual identification of force-onset, while an absolute automated threshold of 40 N does not agree and should not be used interchangeably. Furthermore, the difference between the methods increased in accordance with the magnitude of the threshold (Figure 1), as the 40 N threshold resulted in a greater delay in identification of force-onset than both relative thresholds when compared to manual identification, which in turn increased the force at onset. Despite the relative thresholds agreeing with manual identification of force-onset, all automated methods do not agree with manual identification for F_{50} and F_{150}, as proportional and fixed bias, respectively, were present. As with the force at onset, the difference between methods was greater when using the absolute 40 N threshold in comparison to manual identification, although moderate to large differences in time-dependent force values were found regardless of the threshold used during early portions of the force–time curve (F_{50}, F_{90}, F_{150}). Taken collectively, these results show that strength and conditioning professionals should ensure their chosen method of identifying force-onset is standardised if using the IMTP for the purpose of longitudinal monitoring of force-generating capacity.

The results of the present study support the suggestion by Pickett et al. (2019) that automated relative thresholds may result in greater time-dependent force values when compared to manual identification. In the present study, these differences were greatest during early portions of the force–time curve (Table 1) and were likely due to the differences in the time at force-onset between the automated thresholds and manual identification, which has previously been termed onset bias (Dos'Santos et al., 2017a; Dotan et al., 2016). Although trivial in magnitude, the onset bias inherent to each of the automated thresholds increased the force at onset by ~4–6% and subsequently resulted in moderate to large differences in F_{50} and F_{90} when compared to manual identification (Table 1). Pickett et al. (2019) reported similar differences between the methods, albeit from only two trials and likely affected by a number of previously outlined flaws in testing procedures. The highest time-dependent force values reported by Pickett et al. (2019) were calculated when an absolute 40 N threshold was used to identify force-onset, similar to the results reported in the present study and Dos'Santos et al. (2018). Taken collectively, this suggests that a threshold of a 40 N absolute rise in force results in overestimated assessments of force-generating capacity, likely due to the fixed bias at onset, and therefore its use should be avoided where possible.

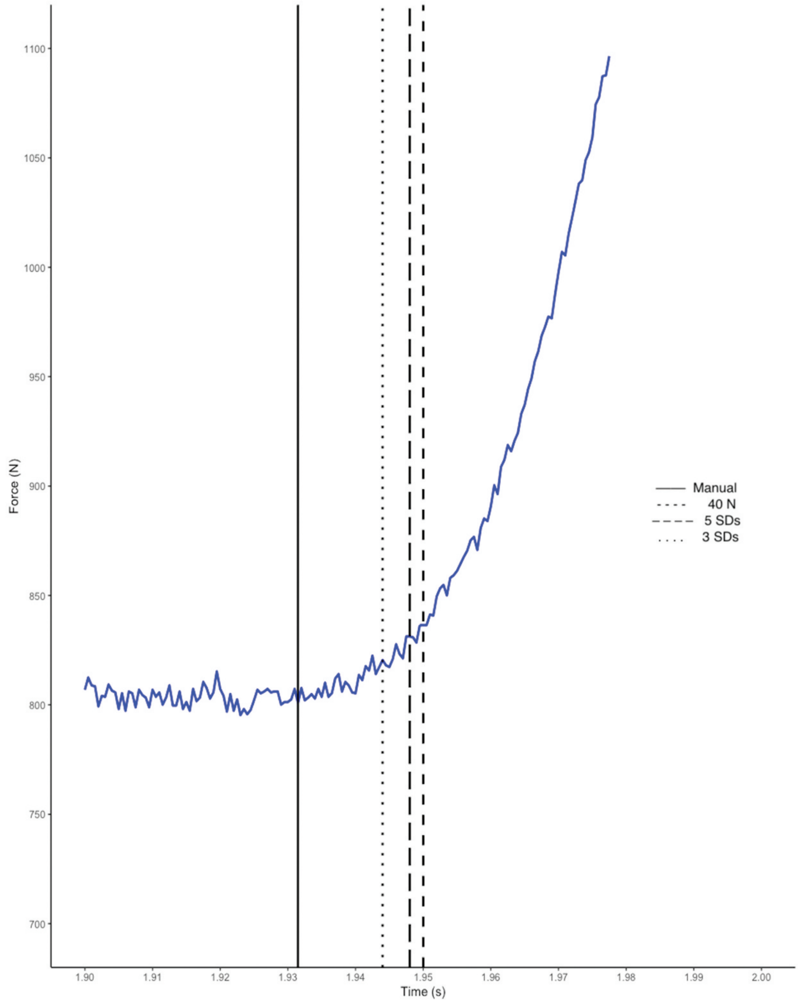

Figure 1. Example isometric mid-thigh pull force–time curve demonstrating the differences in the time at onset between manual identification and thresholds of 40 N above baseline, 5 SDs above baseline, and 3 SDs above baseline.

The results of this study also broadly align with those of Liu et al. (2020), who reported that a 5 SDs BW threshold resulted in large delays in the identification of force-onset and unacceptably biased time-dependent force values when compared to manual identification. Specifically, Liu et al. (2020) reported that both proportional and fixed bias were present between manual identification and 5 SDs for F_{50} and F_{90}. In the present study, we report similar results as the differences in F_{50} between manual identification and 5 SDs increased in proportion to the magnitude of force output. However, we found no fixed bias at this time-point between manual identification and any automated threshold (Figure 4). This proportional increase in F_{50} also occurred when 3 SDs and 40 N were compared to manual identification (Figure 5) and suggests that strength and conditioning professionals should not use manual identification and automated thresholds interchangeably when assessing very early portions of the IMTP

Table 1. Mean bias, 95% limits of agreement, and Hedges *g* effect sizes with 95% confidence intervals comparing manual identification of force-onset and automated thresholds.

	40 N		5 SDs		3 SDs	
Variable	Mean Bias (95% LOA)	Hedges *g* (95% CI)	Mean Bias (95% LOA)	Hedges *g* (95% CI)	Mean Bias (95% LOA)	Hedges *g* (95% CI)
Onset Time (s)	−0.033 (−0.063, −0.003)	−0.021 (−0.043, −0.011)	−0.026 (−0.056, 0.003)	−0.017 (−0.035, −0.009)	−0.022 (−0.049, 0.005)	−0.014 (−0.029, −0.007)
Force at onset (N)	−60.381 (−100.907, −19.856)	−0.399 (−0.593, −0.269)	−44.218 (−82.144, −6.292)	−0.291 (−0.445, −0.187)	−34.684 (−73.352, 3.985)	−0.229 (−0.368, −0.138)
F_{50} (N)	−332.207 (−643.672, −20.742)	−1.075 (−1.404, −0.803)	−265.669 (−571.324, 39.987)	−0.868 (−1.142, 0.655)	−223.526 (−520.812, 73.759)	−0.731 (−0.974, −0.541)
F_{90} (N)	−346.959 (−625.334, −68.583)	−0.692 (−0.900, −0.455)	−289.437 (−566.957, −11.917)	−0.572 (−0.747, −0.363)	−247.978 (−504.170, 8.215)	−0.487 (−0.646, 0.313)
F_{150} (N)	−254.341 (−479.256, −29.425)	−0.404 (−0.573, −0.286)	−214.394 (−431.441, 2.652)	−0.388 (−0.481, −0.235)	−185.376 (−384.127, 13.374)	−0.290 (−0.413, −0.203)
F_{200} (N)	−173.907 (−475.287, 127.473)	−0.279 (−0.463, −0.132)	−147.486 (−418.877, 123.904)	−0.235 (−0.391, −0.106)	−127.171 (−369.479, 115.136)	−0.202 (−0.344, −0.091)
F_{250} (N)	−94.701 (−312.593, 123.190)	−0.144 (−0.314, −0.051)	−88.481 (−284.511, 107.550)	−0.134 (−0.287, −0.050)	−80.947 (−254.172, 92.278)	−0.122 -(0.258, −0.048)

Note: F_{50} = Force at 50 ms; F_{90} = Force at 90 ms; F_{150} = Force at 150 ms; F_{200} = Force at 200 ms; F_{250} = Force at 250 ms; LOA = Limits of agreement; CI = Confidence interval

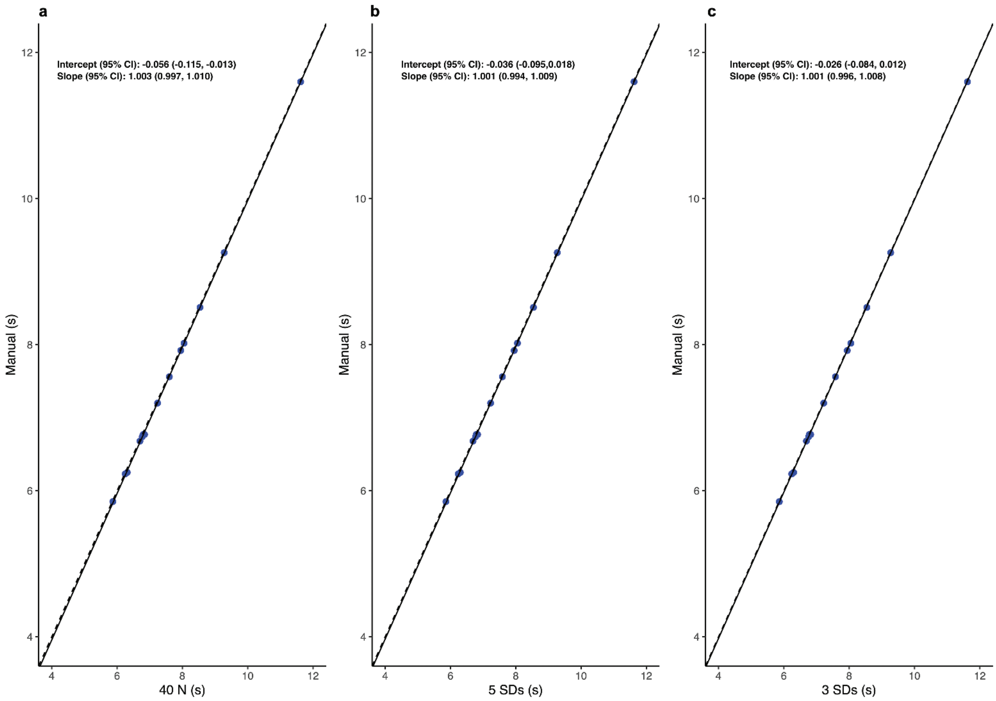

Figure 2. Ordinary least products regression comparisons between manual identification and automated thresholds for time at force-onset. a) Manual v 40 N; b) Manual v 5 SDs; c) Manual v 3 SDs. The solid line represents the ordinary least products regression line and the dashed line represents identity.

force–time curve. Furthermore, fixed bias was found in the present study between each automated method and manual identification for F_{150}, a time-point not investigated by Liu et al. (2020). Where the results of the present study diverge greatest from those reported by Liu et al. (2020) is for F_{200} and F_{250}. Liu et al. (2020) reported that fixed bias was present between manual identification and 5 SDs, while the present study reported no fixed or proportional bias. Furthermore, the mean bias between manual identification and each of the automated thresholds investigated in the present study was below the clinically acceptable difference defined by Liu et al. (2020) for each of these time-points (Table 1). However, even for those time-points where no bias was present when assessed using OLP regression (F_{90}, F_{200}, F_{250}), strength and conditioning professionals should carefully consider based on their practical experience whether the differences in force values reported in the present study allow the relative thresholds to be used interchangeably with manual identification (Bland & Altman, 1986; Ludbrook, 2002). Regardless of the approach chosen by the practitioner, the differences in force-time characteristics between each of the methods make it imperative that they standardise not only their procedures for the performance of IMTP trials (Brady et al., 2020a; Comfort et al., 2019; Guppy et al., 2018), but also their analysis procedures.

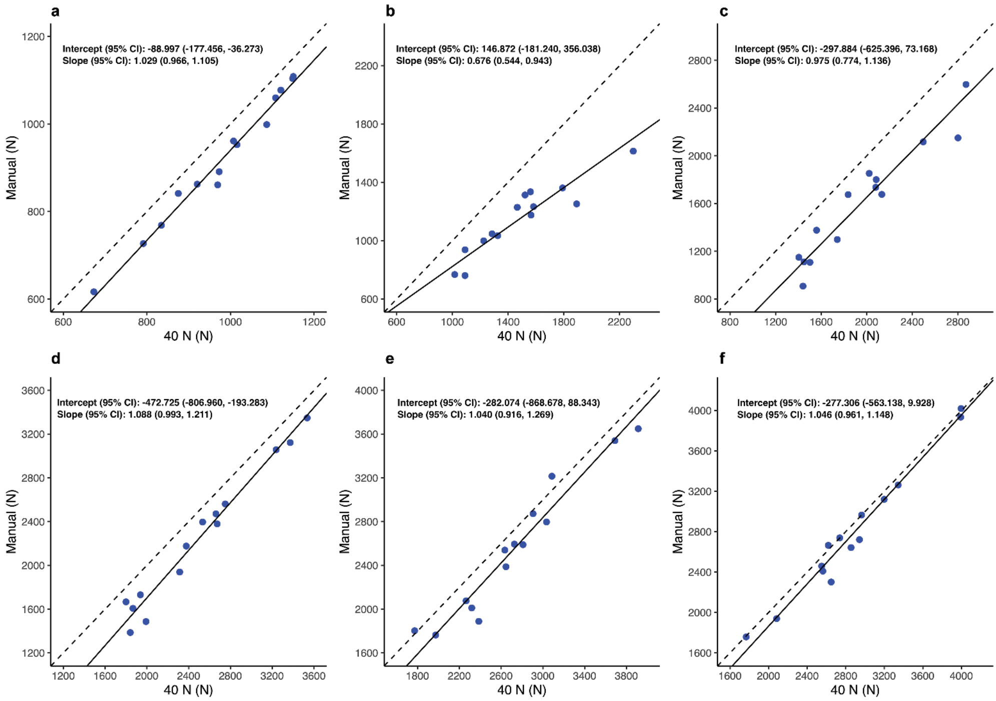

Figure 3. Ordinary least products regression analyses comparing manual identification and a 40 N threshold for force-time characteristics. a) Force at onset; b) Force at 50 ms; c) Force at 90 ms; d) Force at 150 ms; e) Force at 200 ms; f) Force at 250 ms. The solid line represents the ordinary least products regression line and the dashed line represents identity.

Despite the differences in force values between methods of identifying force-onset, it does appear that automated thresholds result in slightly more reliable time-dependent force characteristics, particularly during later epochs—i.e. F_{200}/F_{250}. For example, F_{150} and F_{200} calculated using manually identified force-onset demonstrated good to moderate relative reliability and poor absolute reliability while demonstrating good to excellent relative reliability and moderate absolute reliability when calculated using a threshold of 40 N (Figure 6). Similarly, slight improvements in reliability were found when F_{200} was calculated using both relative automated thresholds. This was reversed for F_{50}, with manual identification resulting in moderate levels of absolute reliability compared to poor absolute reliability when automated thresholds were used. Of note is that regardless of the method of identifying force-onset, F_{90} was less reliable than previously reported in the literature (Dos'Santos et al., 2017a; Guppy et al., 2019) but more reliable than nearby epochs (force at 100 ms) reported by Pickett et al. (2019). This is likely attributable, at least partially, to a procedural difference. While participants in the present study were afforded three sessions to familiarise themselves with the IMTP, the participants recruited by Pickett et al. (2019) were first introduced to the test in the warm-up for the experimental trials. Given the inherently variable nature of time-dependent force-time characteristics, particularly during the early portions of the force–time curve, it has been suggested that a relatively high degree of familiarisation with the isometric

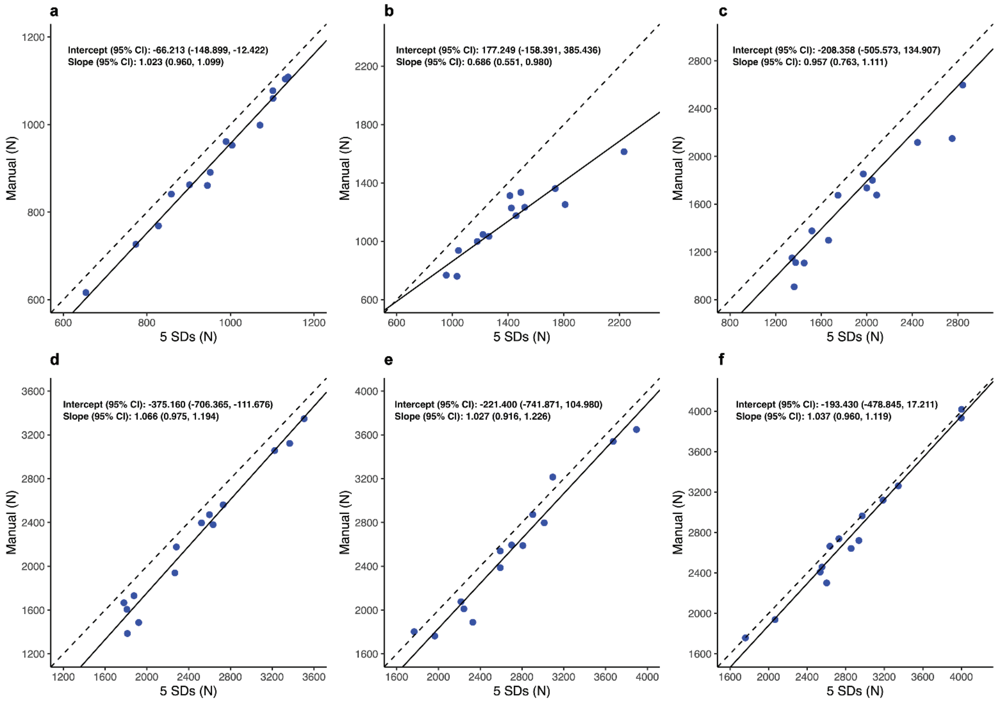

Figure 4. Ordinary least products regression analyses comparing manual identification and a 5 SDs BW threshold for force-time characteristics. a) Force at onset; b) Force at 50 ms; c) Force at 90 ms; d) Force at 150 ms; e) Force at 200 ms; f) Force at 250 ms. The solid line represents the ordinary least products regression line and the dashed line represents identity.

test being performed is required to generate reliable force–time curve data (Drake et al., 2018; Maffiuletti et al., 2016), which likely explains the generally poor reliability results reported by Pickett et al. (2019) for F_{30}, F_{50}, and F_{100}. Furthermore, it highlights that regardless of the method chosen to identify force-onset, strength and conditioning professionals should provide some level of familiarisation prior to using the IMTP as part of their assessment and monitoring regime to ensure measurement error is minimised.

Although efforts were made to control confounding factors over the course of this study, there are several limitations that should be noted. All participants who took part in this study were familiar with weightlifting movements and regularly performed them as part of their normal training programme. As noted in previous literature investigating the IMTP (Brady et al., 2018; Guppy et al., 2019), this may improve the reliability of force–time curve data that is generated during the test and therefore the results of this study may not be directly applicable to populations who are unfamiliar with weightlifting movements. The IMTP testing in this study was performed within a custom-designed rack that allows for the bar to be placed at any height, similar to the one first used by Haff et al. (1997) while standing on an in-ground force plate. Furthermore, the force–time curve data were analysed using custom-designed software that allowed the manual identification of force-onset using a magnified view of the force–time curve. Not all strength and conditioning

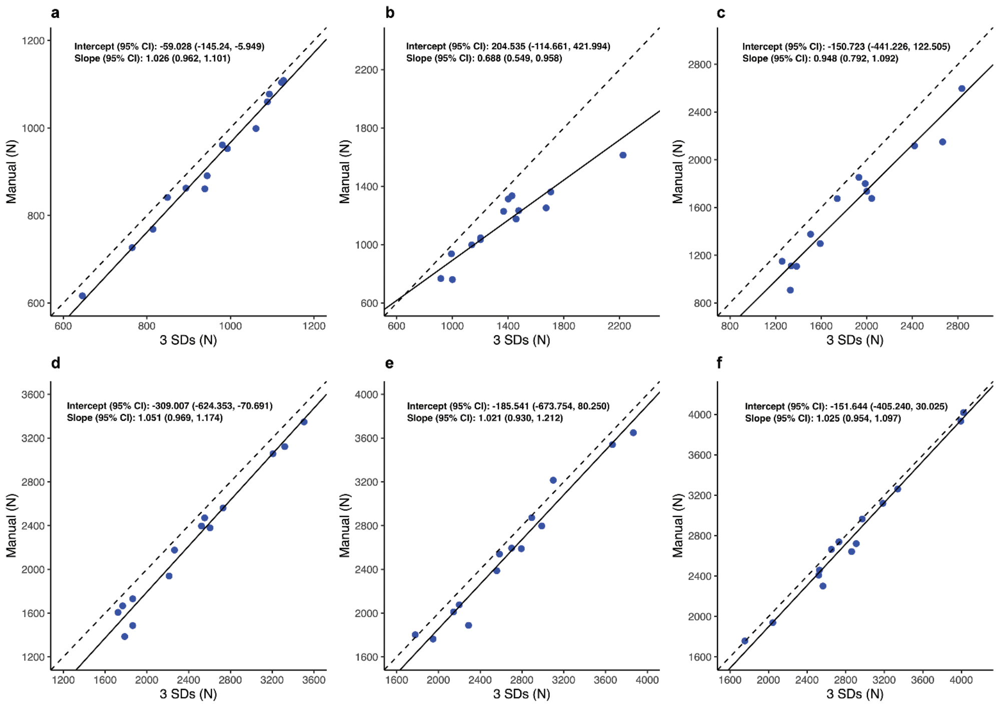

Figure 5. Ordinary least products regression analyses comparing manual identification and a 3 SDs BW threshold for each force-time characteristic. a) Force at onset; b) Force at 50 ms; c) Force at 90 ms; d) Force at 150 ms; e) Force at 200 ms; f) Force at 250 ms. The solid line represents the ordinary least products regression line and the dashed line represents identity.

professionals have access to this equipment or the time and technical proficiency to design custom software in programming languages such as MATLAB or Python therefore may not be able to incorporate manual identification of force-onset into applied practice if only Excel is available. In comparison to the in-ground force-plate and custom-designed IMTP rack used in this study, portable force plates and IMTP racks commonly used in applied settings may have greater signal noise, potentially affecting the accuracy of the 'bodyweight' calculated during the 1 s quiet standing period or requiring the application of filtering to reduce signal noise which has been shown to result in small shifts in onset bias when using relative thresholds (Dos'Santos et al., 2018). Finally, given the degree of subjectivity inherent to manual identification of force-onset, it is possible that there will be some variation in the identified moment of force-onset between strength and conditioning professionals, with the accuracy of the method at least partially dependent on the experience of the individual performing the analysis. At present, the level of experience required to result in consistently accurate manual identification of IMTP force-onset is unknown and warrants future investigation.

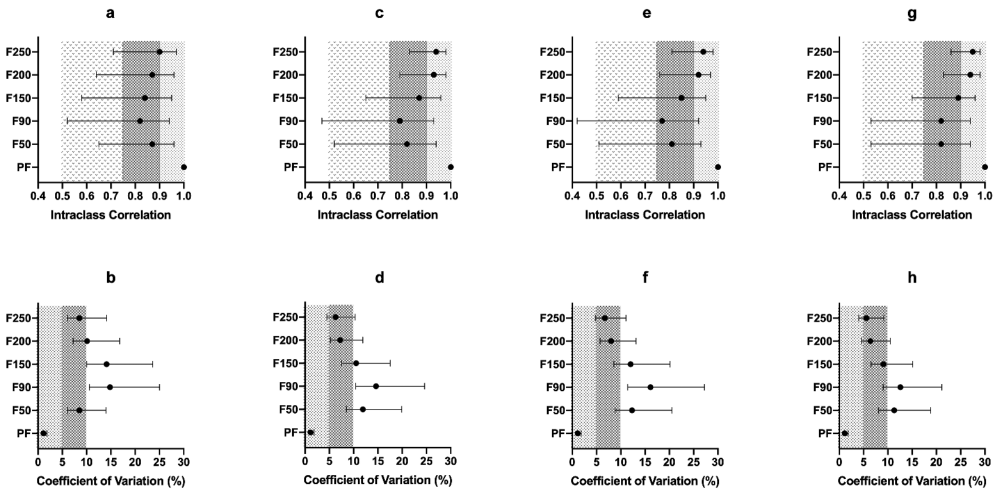

Figure 6. Reliability statistics for force characteristics calculated using each of the four force-onset identification methods. The shaded areas represent the different levels of relative and absolute reliability (ICC < 0.5 = poor; ICC 0.5–0.75 = moderate; ICC > 0.75–0.9 = good; ICC > 0.9 = excellent; CV < 5% = good; CV 5–10% = moderate; CV > 10% = poor); error bars represent 95% confidence intervals. a) ICC force characteristics using visual identification, (b) CV %, (c) ICC force characteristics using the 5 SDs threshold, (d) CV %, (e) ICC force characteristics using the 3 SDs threshold, (f) CV %, (g) ICC force characteristics using the 40 N threshold, (h) CV %. PF = Peak force; F50 = force at 50 ms; F90 = force at 90 ms; F150 = force at 150 ms; F200 = force at 200 ms; F250 = force at 250 ms; CV = coefficient of variation; ICC = Intraclass correlation coefficient.

Conclusions

When analysing force–time curve data generated during the IMTP, strength and conditioning professionals should be aware that although relative thresholds of 5 SDs and 3 SDs of BW agree with manual identification for time at force-onset, they do not agree for force at 50- and 150 ms. Even for those time-dependent measures where no fixed or proportional bias was detected, substantial differences in force values were found between methods. This requires strength and conditioning professionals to carefully consider whether these methods could be used interchangeably if attempting to compare their athletes to normative data or to results reported within the scientific literature. It is also important that when the IMTP is used as a tool for the longitudinal assessment of athlete's force-generating capacity, the method of analysing trials is standardised between testing sessions. This will ensure that changes in physical capacity revealed during the test are not masked or falsely identified by changes in the analysis procedure. Furthermore, researchers should clearly state how force-onset is identified within future studies incorporating the IMTP as a performance test so that worthwhile comparisons can be made between results. The intra- and/or inter-rater reliability should also be reported where researchers manually identify force-onset.

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