International Journal of Strength and Conditioning

McCormick, B. J., MacMahon, C., Talpey, S. W., James, L. P. (2022).The Influence of Instruction on Isometric Mid-Thigh Pull Force-Time Variables. International Journal of Strength and Conditioning
https://doi.org/10.47206/ijsc.v2i1.134

The Influence of Instruction on Isometric Mid-Thigh Pull Force-Time Variables

Brian J. McCormick[1,2], Clare MacMahon[1], Scott W. Talpey[3], Lachlan P. James[1]

[1]Sport and Exercise Science; School of Allied Health, Human Services and Sport; La Trobe University, VIC, Australia, [2]Melbourne City Football Club, Melbourne, Australia, [3]School of Science, Psychology and Sport, Federation University Australia, VIC, Australia

ABSTRACT

Purpose: The isometric mid-thigh pull (IMTP) is commonly used to assess maximal and rapid (i.e., explosive) strength in athlete populations. The conventional IMTP instruction is to pull "as hard and fast as possible" (CON). However, previous studies using other isometric tests indicate that the use of 'hard' and 'fast' independently can result in different outcome measures. This investigation assessed the impact of a 'hard' only (HARD) and 'fast' only (FAST) instruction on bilateral IMTP kinetics when compared to the conventional combined instruction. Methods: Over three separate testing sessions, 17 National level, male, youth footballers (age: 16.4±1.3yr, mass: 69.7±8.0kg, height: 1.75±0.07m) completed three trials of the IMTP under each instruction. Peak force (N) and rapid force production, measured as impulse ($N.s^{-1}$) over 50ms, 75ms, 100ms, 150ms, and 200ms were extracted. To determine the presence of a statistical difference between conditions, a repeated measures ANOVA was employed while Cohen's d effects sizes were used to quantify the magnitude of practical difference between each condition. Results: There was no significant or practically relevant impact of instruction condition on peak force ($P > 0.05$, d=0.08-0.27, 1.1-4.0%), or impulse over any time frame ($P > 0.05$, d=0.01-0.16, 0.2-3.4%). Conclusion: Practitioners can be confident that the conventional IMTP instruction appears sufficient to evaluate maximal and rapid maximal strength characteristics, which will reduce the time to conduct testing in this athlete population.

Keywords: strength testing; assessment; impulse; rate of force development

The ability to express force maximally and rapidly is consistently reported as the key physical quality associated with higher-level athletes across a range of sports.[1] The isometric mid-thigh pull (IMTP) test has been identified as a valid, reliable and time efficient option to quantify these force-time characteristics in athlete populations.[2, 3] Measures of both maximal force (the highest force achieved during the test) and explosive (fast) force in isometric conditions can be extracted from the test and these variables have demonstrated strong relationships with many dynamic sporting actions, such as jumping, sprint acceleration, and change of direction ability.[4] As such, the IMTP has become a popular test amongst practitioners within the training environment.

A fundamental element of any performance test is the presentation of verbal instructions. Accurate instructions and cues inform athletes of the physical requirements of the test and have the potential to influence outcome measures in strength and speed-strength assessments (e.g., displacement, speed, force) by modulating, for example, attentional focus.[5, 6] To guide testing procedures, a substantial body of research has investigated the influence of different instructions on performance outcomes in isometric tests.[7-11] Conventionally, the instructions presented to participants before an IMTP focus simultaneously on two distinct descriptors: To apply maximal effort as "hard" and as "fast" as possible.[2, 3, 8] This is in alignment with a 1990 [7]investigation where a combined 'hard and fast' cue led to significantly greater maximal force production, whilst also facilitating near maximal displays of rapid force production within an isometric finger and wrist flexor task. However, within isometric leg and knee extension actions, more recent studies have reported that a cue which encourages only "fast" force production can enhance rapid force production without decrements in maximal strength when compared to a "hard and fast" cue.[9-11] Furthermore, within the isometric squat test it appears that the order of 'hard' and 'fast' within the instruction may have an impact on both maximal and rapid isometric force measurements. However, the different prescribed effort duration between conditions (1 s vs 3 s) may have impacted these findings rather than the verbal instruction itself.[12] It is therefore unclear if a 'hard' only or 'fast 'only instruction would result in different measurement outcomes in the IMTP when all other methodological elements are held constant.

As test methodologies influence test outcomes, practitioners must understand how their cues may influence variables of interest. The cue that maximizes the variable of interest would seem logical to use in that testing protocol. By understanding the association between a given instruction and performance outcomes then practitioners can confidently use testing results to guide their training prescription. Without valid testing procedures, the information acquired can be misleading and impede the training process. [13] It remains unknown whether the conventional IMTP instruction is optimal for facilitating expressions of both maximal strength and rapid force production. As the IMTP is a staple of athlete assessment models this is a major gap in knowledge, which will impede practice across all levels. Therefore, the aim of this study is to establish whether instructions containing only the "hard" or "fast" descriptor influence peak force and rapid force production variables when compared to the conventional "hard and fast" instruction during the IMTP. It was hypothesized that a difference would be present between groups for both peak and rate dependent metrics. In particular, the "fast" instruction would result in greatest rapid force production, while the greatest peak force would be produced following the 'hard' protocol.

METHODS

Experimental Approach to the Problem

A within-subjects, repeated-measures design was used to determine the effect of instruction on IMTP derived variables. All subjects were familiarized with the protocols of the test over a two-week period. Familiarization for each subject involved two sessions on separate days, in which the procedures were explained, and multiple sub-maximal and maximal attempts were completed with feedback from an accredited strength and conditioning coach. Over a one-week testing period, all subjects completed three testing sessions, one with each of the "hard", "fast", or conventional "hard and fast" instructions. Each testing session was separated by 24 hours and carried out at the same time of day, prior to further training commitments. The sequence of instructions was randomized for each subject to control for order effects. Each subject completed a standardized warm up before each testing session.

Subjects

Seventeen male, national level youth association football (soccer) players from the same club (age: 16.4±1.3yr, mass: 69.7±8.0kg, height: 1.75±0.07m), with at least one-year resistance training experience with a strength and conditioning coach completed the IMTP in all conditions. Subjects were in-season and engaged in football sessions 5 days per week, as well as resistance training 4 days per week. After an explanation of all testing procedures, risks and benefits of participation, consent was gained from each athlete, their guardian, and the sporting institution with which they were associated. The research was approved by the La Trobe University Human Research Ethics Committee.

Testing Procedures

Subjects completed a standardized warm up, consisting of 5-min stationary cycling at 60rpm, 10 alternating bodyweight lunges, 10 bodyweight squats and three IMTP attempts at 60%, 75%, and 90% of maximal perceived exertion. Before each trial each subject then positioned themselves on a dual force-platform system (FDLite Dual Force Platforms, Vald Performance, Albion, Australia) for a period of quiet standing to attain body weight, which was included in the peak force measurements. After weighing, the height of the bar was adjusted to reflect the start of the preferred second pull position during the clean.[3] Each subject had experience with weightlifting movements, and thus all were familiar with this position. This resulted in knee and hip angles between 125-145° and 140-150° respectively. Knee and hip angles were recorded using a goniometer and standardised between trials and sessions. Trials were performed on a custom made, portable rig, which allowed stepwise changes in bar height while the bar was made out of 4140 high tensile steel. Once in position, the subjects gripped the bar with their hands slightly wider than hip width apart and were then secured to the bar with lifting straps. To maintain a high level on consistency and to ensure the objective of the test was understood, participants were presented with an audio recording stating the general instruction, "when you pull, we will be measuring how much force you can produce, as well as how quickly you can produce that force". This was immediately followed by either i) the conventional instruction: "focus on pulling as *hard* and as *fast* as possible" (CON);[14, 15] ii) the instruction: to "focus on pulling as *fast* as possible" (FAST); or iii) the instruction to "focus on pulling as *hard* as possible" (HARD). Following each instruction, the tester provided a countdown and a signal to pull with each pull lasting four seconds. Data were recorded at 1000Hz using native software (NMP ForceDecks v1.2.6780).[16] The participants completed three attempts under each condition, with three minutes of passive recovery between efforts. Trials were discarded and repeated if there was a visible countermovement at the start of the pull or if a trial was exceeded by another by >250 N another. The delivery of instructions was repeated prior to the beginning of each pull and no additional encouragement or feedback was given throughout the testing. Data associated with the two best IMTPs – as determined by peak force - for each subject, in each condition, were exported, averaged, and analysed. The variables analysed from each trial were absolute peak force (N) which represented maximal strength, and impulse ($N \cdot s^{-1}$) over 50ms, 75ms, 100ms, 150ms and 200ms which reflected rapid force production. Each of these metrics were calculated using algorithm-based thresholds in the NMP ForceDecks software (NMP ForceDecks v1.2.6780), which has previously demonstrated strong reliability. [16]

Statistical Analyses

The reliability for each outcome variable across all conditions was assessed via absolute agreement, 2-way mixed-effects intra-class correlation coefficients (ICC) and coefficient of variation expressed as a percentage (CV%). Measures were deemed reliable when the ICC>0.70 and the CV <10%.[17] Data were assessed for normality via a Shapiro-Wilk test with all variables presenting a normal distribution. A repeated measures ANOVA was executed to model a main effect of instruction followed by a Tukey's post-hoc analyses to detect the presence of a significant between any two of the three instruction conditions. An alpha level of 0.05 was set for all null-hypothesis tests. Effect sizes were calculated via Cohen's *d* and classified using the following thresholds: ≤0.19 = *trivial*, 0.20-0.49 = *small*, 0.5-0.79 = *moderate*, and ≥ 0.8 = *large* (7).[18] The ANOVA and associated post-hoc testing was performed using Jamovi statistical analysis software (Jamovi, version 1.1.4.0). Effect sizes were calculated in Microsoft Excel (Microsoft Corporation, Redmond, Washington, US, version 1909) and are reported with their respective 95% CIs. The minimum change needed to exceed the CV% for each variable was considered the threshold for practical relevance. [19]

RESULTS

Within session performances for absolute peak force were highly reliable across conditions (ICC 0.92-0.96; CV 3.4-5.1%; Table 1). Time-dependent impulse achieved either high or acceptable reliability at all timepoints; however, the early-stage measures generally demonstrated the lowest ICC scores, ranging from 0.74-0.80 for impulse at 50ms to 0.80-0.92 when measured to 200ms. The CV ranged from 4.1 to 7.8% across all measures and conditions (Table 1).

A repeated measures ANOVA revealed no main effect of instruction on peak force (P > 0.05) (Figure 1). The effect sizes between each condition indicated no practically relevant differences and ranged from trivial to small (CON vs FAST, d=0.08 [-0.15-0.31], CON vs HARD, d=0.19 [-0.03-0.42], FAST vs HARD d=0.27 [0.04-0.49]), (Table 2). Most (9/17) participants performed their best following the FAST instruction. Following the CON and HARD instructions, 6/17 and 2/17 participants produced their best peak force result, respectively (Figure 2).

No main effect of instruction was present across any impulse time domains (Table 2). Similarly, only trivial effects were revealed between each instruction condition at each impulse epoch. Furthermore, there was a relatively even spread of best individual performances between each group at each time point (Figure 2).

Table 1. Within session intra-class correlation coefficient (ICC) and coefficient of variation expressed as a percentage (%) ± 95% confidence intervals (95% CI), and smallest detectable change for each measured isometric mid-thigh pull (IMTP) variable.

IMTP Variable	ICC (95% CI)	CV% (95% CI)	Smallest Detectable Change
Impulse at 50ms (N·s¹)			2.5 N·s¹/ d>0.61
Conventional	0.73 (0.36-0.89)	5.3 (3.6-12.0)	
Hard	0.80 (0.53-0.92)	4.1 (2.7-9.4)	
Fast	0.74 (0.41-0.89)	7.7 (4.9-17.6)	
Impulse at 75ms (N·s¹)			3.8 N·s¹/ d>0.54
Conventional	0.81 (0.52-0.92)	5.2 (3.8-8.4)	
Hard	0.86 (0.65-0.94)	4.4 (2.8-9.9)	
Fast	0.82 (0.57-0.93)	6.1 (3.9-14.0)	
Impulse at 100ms (N·s¹)			5.6 N·s¹/ d>0.48
Conventional	0.84 (0.60-0.94)	5.4 (3.9-8.7)	
Hard	0.88 (0.71-0.95)	4.6 (2.9-10.4)	
Fast	0.82 (0.57-0.93)	5.6 (3.6-12.7)	
Impulse at 150ms (N·s¹)			11.4 N·s¹/ d>0.44
Conventional	0.87 (0.66-0.95)	6.5 (4.7-10.4)	
Hard	0.91 (0.77-0.96)	5.1 (3.3-11.6)	
Fast	0.78 (0.50-0.91)	6.0 (3.8-13.7)	
Impulse at 200ms (N·s¹)			20.4 N·s¹/ d>0.44
Conventional	0.87 (0.67-0.95)	7.8 (5.7-12.6)	
Hard	0.92 (0.80-0.97)	5.2 (3.3-11.8)	
Fast	0.80 (0.54-0.92)	5.5 (3.5-12.6)	
Peak Force (N)			105.0 N/ d>0.28
Conventional	0.95 (0.86-0.98)	3.9 (2.8-6.2)	
Hard	0.92 (0.80-0.97)	5.1 (3.7-8.1)	
Fast	0.96 (0.89-0.98)	3.4 (2.5-5.4)	

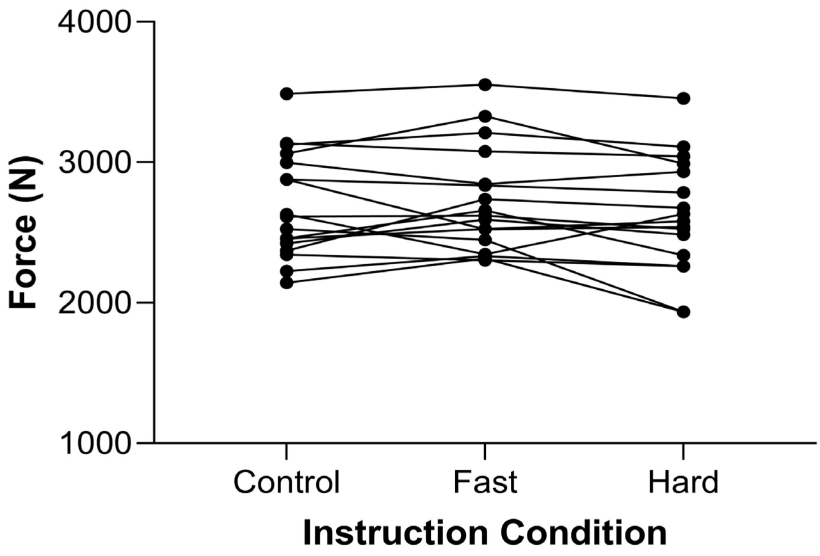

Figure 1. Individual responses in peak force to each instruction condition. No significant differences were observed.

Table 2. Group mean (± SD) impulse (N·s-1) and peak force (N) recorded in each condition, analysed by repeated measures ANOVA and Cohens d effect size (± 95% CI). No significant differences were observed.

Variable	Result	ANOVA	Cohen's *d* Effect Size	
Impulse at 50ms (N·s^{1})				
Conventional	46.98±4.03		Hard vs Con	-0.03 [-0.41-0.37]
Hard	46.86±5.12	P > 0.05	Fast vs Hard	0.04 [-022-0.31]
Fast	47.08±5.46		Fast vs Con	0.02 [-0.34-0.39]
Impulse at 75ms (N·s^{1})				
Conventional	73.56±7.00		Hard vs Con	-0.02 [-0.32-0.35]
Hard	73.42±9.16	P > 0.05	Fast vs Hard	0.08 [-0.15-0.31]
Fast	74.16±9.33		Fast vs Con	0.07 [-0.25-0.40]
Impulse at 100ms (N·s^{1})				
Conventional	103.80±11.62		Hard vs Con	-0.01 [-0.29-0.31]
Hard	103.67±15.23	P > 0.05	Fast vs Hard	0.11 [-0.11-0.33]
Fast	105.38±15.29		Fast vs Con	0.12 [-0.20-0.44]
Impulse at 150ms (N·s^{1})				
Conventional	175.76±26.38		Hard vs Con	-0.02 [-0.25-0.29]
Hard	175.21±33.46	P > 0.05	Fast vs Hard	0.15 [-0.08-0.38]
Fast	180.01±32.34		Fast vs Con	0.15 [-0.17-0.46]
Impulse at 200ms (N·s^{1})				
Conventional	261.46±47.05		Hard vs Con	-0.04 [-0.20-0.28]
Hard	259.36±56.70	P > 0.05	Fast vs Hard	0.16 [-0.06-0.39]
Fast	268.08±52.77		Fast vs Con	0.13 [-0.16-0.43]
Peak Force (N)				
Conventional	2692±378		Hard vs Con	-0.19 [-0.03-0.42]
Hard	2617±410	P > 0.05	Fast vs Hard	0.27 [0.04-0.49]
Fast	2721±376		Fast vs Con	0.08 [-0.15-0.31]

Table 3. Percentage change in group mean(±SD) impulse (N·s-1) and peak force (N) between each condition.

Variable	*% Difference*
Impulse at 50ms ($N \cdot s^{1}$)	
Hard vs Conventional	-0.26±8.29%
Fast vs Hard	+0.46±6.84%
Fast vs Conventional	+0.21±7.87%
Impulse at 75ms ($N \cdot s^{1}$)	
Hard vs Conventional	-0.21±8.09%
Fast vs Hard	+1.00±6.55%
Fast vs Conventional	+0.87±7.62%
Impulse at 100ms ($N \cdot s^{1}$)	
Hard vs Conventional	-0.13±8.50%
Fast vs Hard	+1.66±7.40%
Fast vs Conventional	+1.50±8.73%
Impulse at 150ms ($N \cdot s^{1}$)	
Hard vs Conventional	-0.31±9.99%
Fast vs Hard	+2.74±9.65%
Fast vs Conventional	+2.36±10.81%
Impulse at 200ms ($N \cdot s^{1}$)	
Hard vs Conventional	-0.81±10.46%
Fast vs Hard	+3.36±10.55%
Fast vs Conventional	+2.47±11.31%
Peak Force (N)	
Hard vs Conventional	-2.86±7.63%
Fast vs Hard	+3.99±8.83%
Fast vs Conventional	+1.09±7.16%

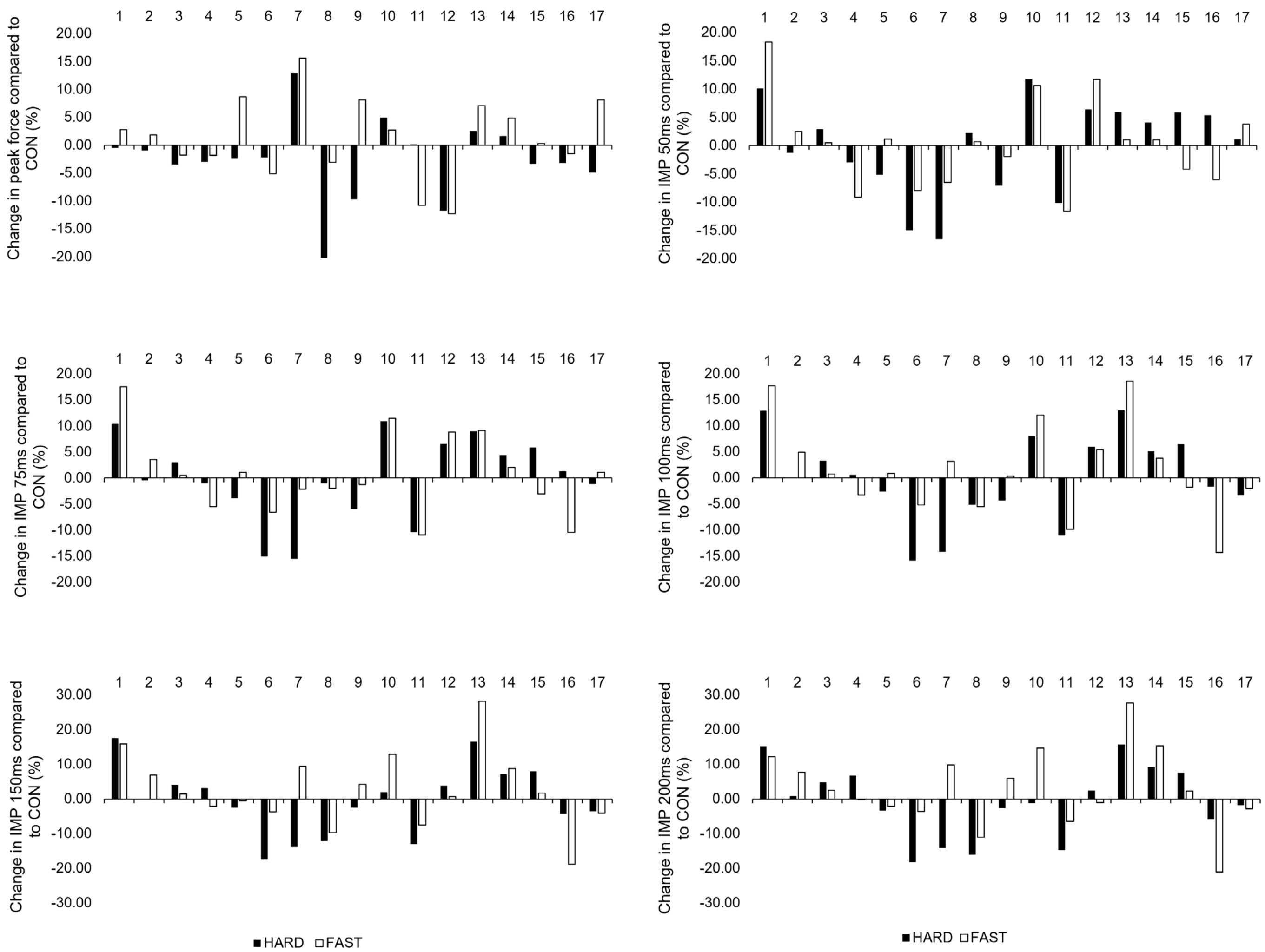

Figure 2. Percentage change for each of the 17 subjects following the 'HARD' and 'FAST' instructions, compared to the conventional instruction (CON) for each variable. IMP: Impulse.

DISCUSSION

The aim of this study was to determine the impact of three different instructions on maximal and rapid force production in the IMTP amongst elite junior soccer players. In this cohort, instruction had no statistical or practical impact on either maximal force or fast force production at the group level and therefore the hypothesis is not accepted. However, most (n=9) participants expressed their highest peak force following the FAST instruction, while only two of the 17 players achieved their best peak force in the HARD condition. From a practical perspective, the findings of this study suggest that when assessing national level academy (age = 16.4±1.3yr) soccer players via the IMTP, practitioners can have confidence that the choice of a hard, fast or hard and fast instruction will have negligible impact on results at the group level. Nonetheless, because individual variation was demonstrated, it is important that practitioners standardise their verbal instructions when longitudinally monitoring force-time characteristics.

While the lack of difference in peak force between conditions is in agreement with most recent studies,[9-11] they are inconsistent with earlier findings of improved measures of rapid force production following a 'fast' instruction.[7, 9-11] There are several methodological differences between this present investigation and earlier studies that may have contributed to the discrepancy in findings. The IMTP is an upright multi-joint isometric test that replicates a common athletic position, and therefore shares associations with dynamic performance measures.[4] In contrast, the isolated tests used in the previous studies, such as finger and wrist flexion,[7] knee extension[9, 10] and seated leg extension[11] have limited relationships to dynamic, sports specific actions. Furthermore, the rate, magnitude, and variability of force expression in an upright, multi-joint test like the IMTP differs considerably from more isolated isometric tests. Only two previous studies have tested the instructions in question on a multi-joint, lower-body test, with one of those being a seated leg extension.[11] The relationship of the seated leg extension to dynamic performance is also unclear, however,[4] and it is not a test that can feasibly be used to assess squads of athletes in the training environment. In addition, the seated position adopted in this test, versus the upright IMTP, may further limit the conclusions that can be drawn in this context.

Findings of improved rapid and maximal force production following fast and hard type instructions, respectively have been demonstrated in the isometric squat.[20] Although the isometric squat is upright, multi-joint test with strong correlations to dynamic performance, similar to the IMTP, there are differences between the two tests.[21] For example, commonality between the two tests for peak force is approximately 50%, while RFD is < 14%.[21] This leaves much of the variance unexplained and demonstrates that results from one do not necessarily translate to the other. Further research is needed to explore the differences between in IMTP and isometric squat variables in response to instruction.

In addition to the test itself, another unique feature of this study was the chosen method of measuring rapid force production. Impulse was recorded at pre-determined time points over the early stages of the pull, in line with recommendations in recent reviews which found this approach to be more reliable than the use of RFD calculated over a moving window (i.e., maximal-RFD).[2, 3] In the current study, there was no significant improvement in rapid force production following the FAST instruction. This contrasts with previous investigations which used the maximal-RFD method. Across both studies by Jaafar et al., [9, 10] and the bilateral leg press test of Sahaly et al.,[11] a 20ms moving window was used to quantify maximal-RFD. Results reported across each of these studies showed that maximal-RFD was 30-50% higher favouring the "fast" instruction. In comparison, Bemben et al.[7] employed a larger 60ms window and reported results that ranged only 5-7% in favour of the "fast" instruction. Maximal-RFD is less stable than other methods of rapid force measurement,[2] which is demonstrated by the poor reliability reported in Jaafar et al., [9, 10] whilst only assumptions can be made about Sahaly et al.[11] as none was reported. The frequent reports of reduced reliability associated with maximal-RFD in multi-joint isometric tests [20, 22] is the primary reason it is not recommended in contemporary protocols.[2, 3] Using a more reliable methodology for measuring rapid force production, this study was unable to detect differences on the basis of instruction.

There are confounding factors that may have impacted the results of this study. First, consideration must be given to the effect of concurrent training load on explosive neuromuscular performance. Testing occurred across a period in which the players also completed a high volume of endurance exercise as part of their sport specific training programme, alongside four resistance training sessions per week. Such a high volume of training almost certainly led to levels of fatigue, dampening muscle activation and motor unit recruitment.[23-25] This likely inhibited rapid force production, [26, 27] blunting the subjects' ability to exert force rapidly and maximally[24, 28] and, in turn, dampening the differences in force expression between conditions. It is also worth noting that strength qualities become more distinct as strength capacity and resistance training age increase.[29] Therefore, athletes in sports with greater strength demands than soccer might demonstrate a different result. From a protocol perspective, future studies could consider randomising the testing, however in team-based strength and conditioning settings, this is not always feasible.

Three recent studies have reported that a shorter trial duration may result in heightened expressions of rapid force production in multi-joint isometric tests[12, 20, 30] .Drake et al.[20] and Suarez et al.[12] found that a 1-second trial period improved reliability and magnitude of RFD and impulse recordings. Of particular relevance, Drake et al.[20] demonstrated that an instruction emphasizing a "fast" effort was associated with increases in rapid force production, whilst a 'hard' instruction improved maximal strength expression. However, as improved rapid force production was also seen in Suarez et al.,[12] with the same instruction across both contraction periods, it is unclear whether the result was due to instruction alone. Further investigations using these shorter trial periods are necessary to better understand the implications on outcome metrics, reliability, and the acute fatigue resulting from the test.

PRACTICAL APPLICATIONS

Practitioners can be confident that the conventional 'hard and fast' instruction used in the IMTP is suitable and there is no need to decouple the terms 'hard' and 'fast' to achieve a superior result in peak force or rapid force metrics. This enables efficient testing of athletes as the "hard and fast" instruction negates the need for multiple IMTP tests with different instructions to assess maximal and explosive strength separately. Finally, as a degree of variation between individuals was present across conditions, practitioners must remain consistent with the instructions they use.

CONCLUSION

This study investigated the impact of a 'hard' or 'fast' cue, with respect to a conventional 'hard and fast' instruction, on IMTP performance. The results demonstrated no statistical or practical difference in maximal or rapid force production during the IMTP on the basis of a 'hard', 'fast' or 'hard and fast' instruction. However, further investigations are needs to determine the impact of strength level on the IMTP force-time characteristics in response to these alternate verbal instructions.

REFERENCES

1. Suchomel TJ, Nimphius S and Stone MH. The Importance of Muscular Strength in Athletic Performance. Sports Med 2016; 46: 1419-1499.
2. Brady CJ, Harrison AJ and Comyns TM. A review of the reliability of biomechanical variables produced during the isometric mid-thigh pull and isometric squat and the reporting of normative data. Sports Biomech 2020; 19: 1-25. DOI: 10.1080/14763141.2018.1452968.
3. Comfort P, Dos'Santos T, Beckham GK, et al. Standardization and Methodological Considerations for the Isometric Midthigh Pull. Strength Cond J 2019; 41: 57-79. DOI: 10.1519/ssc.0000000000000433.
4. Lum D, Haff GG and Barbosa TM. The relationship between isometric force-time characteristics and dynamic performance: a systematic review. Sports 2020; 8: 63.
5. Wulf G, Shea C and Park J-H. Attention and motor performance: Preferences for and advantages of an external focus. Res Q Exerc Sport 2001; 72: 335-344.
6. Brady C, Comyns T, Harrison A, et al. Focus of attention for diagnostic testing of the force-velocity curve. Strength Cond J 2017; 39: 57-70.
7. Bemben MG, Clasey JL and Massey BH. The effect of the rate of muscle contraction on the force-time curve parameters of male and female subjects. Res Q Exerc Sport 1990; 61: 96-99.
8. Halperin I, Williams KJ, Martin DT, et al. The effects of attentional focusing instructions on force production during the isometric midthigh pull. J Strength Cond Res 2016; 30: 919-923.
9. Jaafar H and Lajili H. Separate and combined effects of time of day and verbal instruction on knee extensor neuromuscular adjustments. Appl Physiol Nutr Metab 2018; 43: 54-62.
10. Jaafar H and Lajili H. The influence of verbal instruction on measurement reliability and explosive neuromuscular performance of the knee extensors. J Hum Kinet 2018; 65: 21.
11. Sahaly R, Vandewalle H, Driss T, et al. Maximal voluntary force and rate of force development in humans–importance of instruction. Eur J Appl Physiol 2001; 85: 345-350.
12. Suarez DG, Carroll KM, Slaton JA, et al. Utility of a Shortened Isometric Midthigh Pull Protocol for Assessing Rapid Force Production in Athletes. J Strength Cond Res 2020; Publish Ahead of Print. DOI: 10.1519/jsc.0000000000003774.
13. Impellizzeri F, Rampinini E and Marcora S. Physiological assessment of aerobic training in soccer. J Sports Sci 2005; 23: 583-592.
14. James LP, Roberts LA, Haff GG, et al. Validity and reliability of a portable isometric mid-thigh clean pull. J Strength Cond Res 2017; 31: 1378-1386.
15. Stone MH, O'Bryant HS, Hornsby G, et al. Using the isometric mid-thigh pull in the monitoring of weightlifters: 25+ years of experience. Professional Strength and Conditioning 2019; 54: 19-26.
16. Carroll KM, Wagle JP, Sato K, et al. Reliability of a commercially available and algorithm-based kinetic analysis software compared to manual-based software. Sports Biomech 2017: 1-9.
17. Atkinson G and Nevill AM. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. Sports Med 1998; 26: 217-238.
18. Cohen J. Statistical power analysis for the behavioral sciences. Academic press, 2013.
19. Turner A, Brazier J, Bishop C, et al. Data analysis for strength and conditioning coaches: Using excel to analyze reliability, differences, and relationships. Strength Cond J 2015; 37: 76-83.
20. Drake D, Kennedy RA and Wallace ES. Multi-joint rate of force development testing protocol affects reliability and the smallest detectible difference. J Sports Sci 2019; 37: 1570-1581.
21. Nuzzo JL, McBride JM, Cormie P, et al. Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. J Strength Cond Res 2008; 22: 699-707. DOI: http://dx.doi.org/10.1519/JSC.0b013e31816d5eda.
22. Haff GG, Ruben RP, Lider J, et al. A comparison of methods for determining the rate of force development during isometric midthigh clean pulls. J Strength Cond Res 2015; 29: 386-395.
23. Fernandes JF, Lamb KL and Twist C. Exercise-induced muscle damage and recovery in young and middle-aged males with different resistance training experience. Sports 2019; 7: 132.
24. Millet GY and Lepers R. Alterations of neuromuscular function after prolonged running, cycling and skiing exercises. Sports Med 2004; 34: 105-116.
25. Škof B and Strojnik V. Neuromuscular fatigue and recovery dynamics following prolonged continuous run at anaerobic threshold. Br J Sports Med 2006; 40: 219-222.
26. Aagaard P, Simonsen E, Andersen J, et al. Increased rate of force development and neural drive of human skeletal muscle following resistance training. J Appl Physiol 2002; 93: 1318-1326.
27. Maffiuletti NA, Aagaard P, Blazevich AJ, et al. Rate of force development: physiological and methodological considerations. Eur J Appl Physiol 2016; 116: 1091-1116.
28. Buckthorpe M, Pain MT and Folland JP. Central fatigue contributes to the greater reductions in explosive than maximal strength with high-intensity fatigue. Exp Physiol 2014; 99: 964-973.
29. James LP, Beckman EM, Kelly VG, et al. The neuromuscular qualities of higher and lower-level mixed martial arts competitors. Int J Sports Physiol Perform 2017; 12: 612-620.
30. Guppy SN, Kotani Y, Brady CJ, et al. The Reliability and Magnitude of Time-Dependent Force-Time Characteristics During the Isometric Midthigh Pull Are Affected by Both Testing Protocol and Analysis Choices. J Strength Cond Res 2022; 36: 1191-1199. DOI: 10.1519/JSC.0000000000004229