Optimizing athlete assessment of maximal force and rate of development:

A comparison of the isometric squat and mid-thigh pull

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ABSTRACT

This study compared force-time characteristics and muscle activity between the isometric squat (ISQ) and mid-thigh pull (IMTP) in both bilateral (ISQ_{BI} and IMTP_{BI}) and unilateral (ISQ_{UNI} and IMTP_{UNI}) stance. Peak force (PF), rate-of-force (RFD) (e.g. 0-300ms) and EMG of the multifidus, erector spinae (ES), gluteus maximus (GM), biceps femoris (BF), semitendinosus (ST), vastus medialis (VM), vastus lateralis (VL) and soleus were recorded in ten recreationally trained males. PF was significantly greater during the ISQ_{BI} vs. IMTP_{BI} ($p=0.016$, $ES=1.08$) but not in the unilateral test mode although effects remained moderate ($ES=0.62$). A trend indicated heightened RFD_{300ms} ($p = 0.083$; $ES=0.81$) during the IMTP_{BI} vs. the ISQ_{BI}, but these effects were smaller in the unilateral test ($ES = 0.51$). Greater ($p<0.0001$) EMG for VL ($ES=1.00-1.13$) and VM were recorded during the ISQ compared to IMTP modes in both modes ($ES = 0.97 - 1.18$). Greater BF EMG ($p = 0.030$, $ES = 0.31$) was shown in IMTP_{BI} vs. ISQ_{BI} and these effects were stronger in the unilateral modes ($p = < 0.05$; $ES = 0.81 - 0.83$). Significantly greater ST activation was shown in both IMTP_{UNI} ($p < 0.05$; $ES = 0.69-0.76$) and IMTP_{BI} ($p < 0.001$; $ES = 1.08$). These findings indicate that ISQ results in elevated PF, whereas, RFD is heightened during the IMTP and these differences are more pronounced in bilateral modes. Greater activation of the quadriceps and hamstring muscles are expected in ISQ and IMPT respectively.

Keywords: isometric strength; rate of force development; unilateral and bilateral

INTRODUCTION

Muscular strength is a fundamental physical quality that underpins sports performance.²³ Rate of force development (RFD) is also of high importance when constraints exist for the time availability of force production.¹⁷ Optimization of these physical characteristics through effective testing allows more targeted training interventions to be implemented.

Recently, there has been an increase in the utilization of maximal strength tests such as the isometric squat (ISQ) and mid-thigh pull (IMTP).^{2,4,6,9,12} These assessments have lower skill requirements than traditional iso-inertial testing and therefore may be more advantageous in settings such as large group programs, rehabilitation and when working with athletes of a low training age.⁵

Numerous studies have included the IMTP,^{6,9,25} with fewer employing the ISQ.^{2,21} Nuzzo et al.²¹ utilized both assessment modes and showed they were significantly correlated ($r = 0.76$); however, peak force and RFD were higher in the ISQ. Greater peak force during the ISQ has also been shown for females only, with a trend evident of higher impulse and RFD during the ISQ but these differences were not significant.⁴ No meaningful differences were observed between the two assessment modes in the male athletes.⁴ Cumulatively, the available evidence comparing force-time characteristics in the two tests are equivocal and require further investigation. Furthermore, previous literature investigating the differences between the ISQ and IMTP have only used a bilateral stance.^{4,21} Given the increased frequency of research pertaining to measurement of unilateral tasks,^{2,3} and their associations with reductions in performance,³ a more comprehensive understanding of these assessment modes is warranted.

In addition to kinetic comparisons, it is necessary to examine the level of muscle activation to further inform practitioners. This information has implications for athlete profiling, longitudinal monitoring and training prescription. In the IMTP, the arms are used to transmit forces from the ground as participants “pull” the bar, whereas in the ISQ the bar is positioned on the upper back.⁴ Although there are clearly similarities between the two actions as indicated by their significant correlation,²¹ the set-up of the IMTP may result in greater recruitment of posterior chain musculature. Conversely, the ISQ may heighten muscle activation of the knee extensors. However, this is currently speculatively and requires data to support this notion.

The purpose of this investigation was to compare the force-time characteristics and muscle activity of selected lower body and trunk muscles during both the unilateral and bilateral ISQ and IMTP. It was hypothesized that test modes would elicit different muscle activation patterns with the squat showing increased quadriceps activation and resultant peak force.

METHODS

Experimental design

A repeated measure, randomized, counterbalanced study design was used to control for exercise order (isometric mid-thigh pull and isometric squat respectively) and mode (unilateral and bilateral). Following a prior familiarization, all recorded tests were subsequently performed in a single testing session. Participants were required to abstain from training for 48 hours prior and asked to maintain a consistent fluid (water only) and dietary intake on the day of testing.

Subjects

Ten recreationally trained participants (age = 37.4 ± 4.1 years; body mass = 74.4 ± 3.9 kg; height = 1.75 ± 0.04 m; body mass index 24 ± 1 kg/m²) with no current musculoskeletal injuries, and a minimum of two years of resistance training experience volunteered to take part. This study was approved by the Anti-Doping Lab, Qatar, IRB: F2017000227 and all the subjects provided informed consent prior to participation. All procedures were conducted in accordance with the Declaration of Helsinki.

Procedures

On arrival, height (Stadiometer: Seca, Birmingham, UK) and body mass were assessed (Seca Digital Scales, Model 707: Seca, Birmingham, UK) measured to the nearest 0.1 cm and 0.1 kg, respectively. Participants first performed a standardized 10-minute general warm-up consisting of pulse raising and dynamic stretches in addition to two practice trials at 60 and 80% of their perceived maximum effort for each exercise condition.

Unilateral and Bilateral Isometric Squat and Mid-Thigh Pull

The IMTP and ISQ were performed in a 'ISO rig' (Absolute Performance, Cardiff, UK) with either one or two single axis force plates (dependent on the test mode) (PASPORT force plate, PASCO Scientific, California, USA) sampling at 1000 Hz, positioned directly underneath the steel bar. Incremental height adjustments of 1 cm were used to accommodate athletes of different statures. Set up protocol was completed in accordance with a recent commentary describing recommended test procedures.⁷ Participants were instructed to maintain an upright torso (forward lean of 5° from vertical) and a manual goniometer was used to record the knee (135° to 140°) and hip (140° to 145°) angle during both the unilateral and bilateral modes. Angles were recorded for each participant and replicated across the different test modes to

allow comparison and ensure standardization. No significant differences were observed between anatomical angles irrespective of test mode (IMTP vs. ISQ) and condition (unilateral vs. bilateral) ($p > 0.05$). During the unilateral testing modes, the non-stance limb hovered next to the working limb to keep the hips level, aiding balance and stability. During the IMTP, participants used lifting straps to ensure grip was not the limiting factor to lower limb strength expression. Grip width and foot position were standardized within participants.⁵

Independently of exercise condition, participants were required to stand in the centre of the force plate and remain motionless for a period of at least 1s prior to the initiation of the test. Participants were instructed take the ‘slack’ from the body while being monitored to maintain minimal pre-tension (verified by manual detection of the force-time curve in real time) ensuring the force trace is similar to body mass and steady.⁷ If an uncontrolled pre-tension (>50 N change) and / or countermovement (e.g. production of a negative/antagonist force) prior the onset of the action was observed, the trial was repeated.⁷ Each trial was initiated by a “3, 2, 1, Go” countdown and participants were instructed to ‘push the ground away by driving their feet into the force plate as fast and hard as possible’.⁷ These instructions have been recommended to maximize both PF and RFD.¹⁷ The participants maintained the effort for 4s with strong and standardized verbal encouragement provided throughout. Two trials were performed, and the mean reported for each condition (right, left and bilateral) with 30 seconds rest between each and 2 minutes’ rest between testing modes.

Recorded metrics included net peak force (PF - body weight) and average rate of force development [(RFD, Δ Force/ Δ time)] at 100, 200, and 300 ms time windows. Contraction onset was determined using 5 standard deviations of body weight recorded during an initial 1s weighing period of quite standing prior to the test initiation.⁸

Electromyography measurement

Data were collected by a sixteen-channel wireless EMG system (DTS, Noraxon USA Inc, Scottsdale, Arizona). Standard skin preparation was completed prior to dual electrode placement (Noraxon USA Inc, Scottsdale, Arizona). Self-adhesive electrodes were attached in parallel to the fibers of the multifidus, erector spinae (longissimus), gluteus maximus, biceps femoris, semitendinosus, vastus medialis, vastus lateralis and soleus on both body sides in accordance with SENIAM guidelines.¹⁴

Raw EMG signals were sent in real time to a computer and recorded at 1500 Hz. The data were recorded and further analyzed by MyoResearch 3.12 software (Noraxon USA Inc, Scottsdale, Arizona). Signals were high pass filtered (10 Hz), rectified and smoothed with a root mean square algorithm with a 100-millisecond window. Mean and maximum EMG data were normalized to the mean peak of a 1000-millisecond window from a 5s maximal voluntary isometric contraction (MVIC) trial for each muscle in accordance with previous guidelines.¹⁴ Mean and peak EMG signal amplitudes over a 3-second window after muscle onset of each condition were calculated and averaged. Muscle onset was determined as a rise at 20% of peak EMG signal of the vastus medialis muscle using MR3.12 software auto-marker algorithm and confirmed by visual inspection.

Statistical analysis

Data are presented as mean $\pm$ standard deviations. The normality distribution of the data was checked with the Shapiro–Wilk test. To examine differences in force-time data and EMG between respective test modes (IMTP vs. ISQ) in both bilateral and unilateral stance (dominant limb), a paired samples t-test was used. Additionally, Cohen ES statistics were calculated and

defined as trivial (< 0.2), small ($0.2 - 0.6$), moderate ($0.6 - 1.2$), large ($1.2 - 2.0$) and very large (< 2.0).¹⁵ Data were analyzed using Microsoft Excel and SPSS software (version 21.0, IBM SPSS Statistics, Chicago, IL, USA).

RESULTS

Force Production

PF and RFD measures during the ISQ and IMTP tests in the unilateral and bilateral modes are presented in Table 1. Data revealed significantly greater PF during the ISQ_{BI} ($p = 0.016$) only. Moderate effect sizes were shown indicating increased PF for ISQ_{UNI} ($ES = 0.62$) and ISQ_{BI} ($ES = 1.08$) respectively. There was a trend to suggest greater RFD300ms during the IMTP_{BI} vs. ISQ_{BI} ($p = 0.083$) with small ($ES = 0.51$) and moderate effects ($ES = 0.81$) reported in the unilateral and bilateral mode comparison respectively. Moderate effects ($ES = 0.63$) were also shown for the IMTP_{BI} vs. ISQ_{BI} assessment of RFD200ms while all other comparisons were non-significant and displayed small effects (< 0.6).

*** Insert table 1 here ***

Muscle Activity

Muscle activation during the ISQ and IMTP exercises in the unilateral and bilateral modes are displayed in Table 2. Greater peak and mean EMG activity of the vastus lateralis and medialis ($p < 0.001$) were present during the ISQ_{UNI} and ISQ_{BI} compared to both IMTP modes, corresponding to a moderate effect ($ES = 0.97 - 1.18$). There was a trend for greater peak EMG activity of the Biceps femoris ($p = 0.051$; $ES = 0.27$) in the IMTP_{BI} compared to the ISQ_{BI} and these differences were significant, but effects were small for mean EMG ($p = 0.030$, $ES = 0.31$). This observed trend became more apparent in the unilateral modes, with significant between

test differences indicating the IMTP_{UNI} resulted in significantly greater peak and mean EMG biceps femoris activity corresponding to a moderate effects size ($p < 0.05$; $ES = 0.81 - 0.83$). When observing the EMG of the semitendinosus muscle, there was a stronger effect of exercise condition, whereby significantly greater peak and mean muscle activation was shown in both IMTP_{UNI} ($p < 0.05$; $ES = 0.69-0.76$) and IMTP_{BI} ($p < 0.001$; $ES = 1.08$) in comparison to both ISQ modes. No meaningful differences or substantial effects were indicated between testing modes for any of the other muscles tested.

***Insert table 2 here

DISCUSSION

The purpose of this investigation was to compare the force-time characteristics and muscle activity of selected lower body and trunk muscles during both the unilateral and bilateral ISQ and IMTP. Greater peak force values were shown during the ISQ versus the IMTP. Conversely, there was a trend for a greater rate of force development (RFD_{300ms}) during the IMTP, with these differences more pronounced when comparing the bilateral exercise modes. Additionally, greater EMG activity of the anterior (vastus lateralis and medialis) and posterior (semitendinosus and bicep's femoris) muscles of the thigh were indicated for the ISQ and IMTP respectively.

The greater sensitivity of the bilateral testing modes to differentiate the force-time characteristics specific to each task may be attributed to the decrease in base of support that occurs during unilateral tasks.¹¹ The increased instability present during single leg stance may effect technique execution, decreasing maximum and rapid force generation.¹¹ Several

investigations have also shown that maximal isometric strength assessments used to calculate RFD are susceptible to enhanced measurement error,¹³ with shorter time-bands appearing to be less reliable for RFD assessment.^{4,5} This lower performance reproducibility could be more evident during unilateral assessments and may in part explain the clearer differences (effect sizes) in RFD observed between the ISQ and IMTP during the bilateral tasks. Cumulatively, this study indicates that force-time characteristics are different between tasks (IMTP vs. ISQ) and to optimize the measurement of maximal force-time characteristics, bilateral tasks may be more advantageous.

Our results confirm recent observations of greater peak force expression during the ISQ.^{4,21} Greater peak forces during ISQ vs. IMTP may be explained at least in part by differences in cross sectional area between the quadriceps vs hamstrings muscles groups.^{22,26} Previous research has indicated that independent of the testing mode (isometric, concentric and eccentric), higher peak forces are reported when measuring force capabilities of quadriceps vs. hamstrings muscles.²⁴ In the current study, heightened recruitment of the quadriceps was shown during the ISQ and this may have resulted in a greater degree of force/tension during the ISQ independently of the testing mode.^{22,26}

An elevated instability component may also affect the magnitude of muscle activation. Heightened recruitment of the quadriceps and hamstring musculature was indicated in both the ISQ_{UNI} and IMTP_{UNI} tasks. There are contradictory reports regarding greater motor unit activation during unilateral vs. bilateral maximal muscle voluntary contractions.^{11,19} Some studies have shown that the concurrent request to stabilize and maximize force production during more unstable exercises may result in decreased activation when compared to those with lower stabilization requirements.¹⁸ Nevertheless, this has not been observed in other

studies.^{11,19,20} Several methodological factors may explain the distinct observations between studies, including ours. These include different loading schemes (maximal voluntary contractions vs. 3RM vs. unweighted), muscle actions applied (e.g. dynamic vs isometric muscle actions) and exercise modes (single vs multi-joint).^{11,18,19,20}

The heightened quadriceps and hamstring recruitment shown during the ISQ and IMTP respectively could also in part be attributed to bar position as this is likely a determinant moderator of the loading requirements in each individual exercise,¹⁶ influencing the kinetic, kinematic and muscle activation patterns.¹⁰ Placing the moment arm further in front of the hip (IMTP) or behind the knee (ISQ) will distinctly affect the muscle recruitment strategy and may explain the observed changes in posterior and anterior muscular recruitment during the IMTP and ISQ respectively.¹⁶

When interpreting the data from the current study, some limitations should be acknowledged. A small sample size was recruited, and the analysis may have been under powered. However, additional statistical analysis was included and effect sizes to provide a clearer interpretation of the data and the strength of any effects identified. In addition, the population tested were resistance trained individuals and not team sport athletes; thus, it is difficult to generalize the findings to the larger population. We included those with substantial resistance training experience to ensure that differences identified between the tests were not based on un-familiarity. However, further research is required in other cohorts to examine if the results are replicated.

CONCLUSIONS

In summary, the results of the current study indicate that unilateral and bilateral ISQ results in greater absolute peak force values, whereas, RFD is heightened during the IMTP. The bilateral exercise modes seem to further optimize the assessment of these the distinct force-time

characteristics. The muscle activity may also vary between tasks with the ISQ resulting in a greater activation of the quadriceps muscles and the IMTP of the hamstring muscles.

Using these data, assessments can be tailored according to individual needs of the athlete based on the sport demands and if maximal strength is monitored during injury rehabilitation. The data indicate that bilateral variations are preferred to measure an individual's true maximum strength (ISQ) and RFD capacity (IMTP). In addition, the greater quadriceps activation during the ISQ and higher peak forces may have connotations for athletes where quadriceps strength may be deficient; such as, following anterior cruciate ligament reconstruction.

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Table 1. Peak Force and rate of force development during the different exercise modes (mean $\pm$ SD)

	Unilateral (n = 18)			Bilateral (n = 9)		
	IMTP _{UNI}	ISQ _{UNI}	Δ	IMTP _{BI}	ISQ _{BI}	Δ
Peak Force	1456 (189)	1612(284) *	10.7%	1771 (171)	2111 (310) *	19.2%
RFD 100 ms	2730 (1091)	2755 (1265)	0.9%	4364 (1882)	3450 (13851)	-20.9%
RFD 200 ms	2971 (980)	2814 (847)	-5.3%	4358 (1174)	3651 (1221)	-16.2%
RFD 300 ms	2888 (854)	2555 (724)	-11.5%	3935 (1012)	3151 (950)	-19.9%

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RFD - rate of force development; IMTP - isometric mid thigh pull; ISQ - isometric squat; Uni- unilateral; BI - bilateral * <0.05 significant difference from IMTP

Table 2. Surface electromyography data recorded during the different exercise modes (mean $\pm$ SD)

	PEAK EMG (%MVIC)			MEAN EMG (%MVIC)			PEAK EMG (%MVIC)			MEAN EMG (%MVIC)		
	IMTP _{UNI}	ISQ _{UNI}	Δ	IMTP _{UNI}	ISQ _{UNI}	Δ	IMTP _{BI}	ISQ _{BI}	Δ	IMTP _{BI}	ISQ _{BI}	Δ
Erector Spinae	83.95 (22.3)	80.1 (36.3)	-2.1%	40.7 (12.4)	39.1 (24.8)	-0.5%	113.8 (32.5)	105.0 (34.4)	-7.9%	71.1 (18.7)	60.3 (19.8)*	-8.6%
Multifidus	95.9 (32.9)	93.9 (42.9)	-4.5%	55.9 (20.1)	55.6 (29.7)	-3.9%	114.1 (31.7)	105.6 (36.6)	-7.1%	72.9 (19.8)	66.6 (27.5)	-15.2%
Gluteus Maximus	98.2 (41.0)	100.6 (74.1)	2.4%	57.9 (25.3)	60.3 (47.4)	4.1%	43.7 (19.8)	41.9 (26.3)	-4.1%	23.3 (9.2)	24.3 (16.4)	4.3%
Biceps Femoris	121.8 (48.8)	85.4 (31.7)*	-29.9%	76.5 (32.8)	51.3 (21.6)*	-32.9%	46.4 (33.0)	37.2 (22.5)	-19.8%	25.4 (20.5)	20.1 (15.5)	-20.9%
Semitendinosus	74.4 (18.4)	60.1 (36.1)	-19.2%	44.2 (11.2)	34.3 (22.4)*	-22.4%	51.3 (14.0)	34.7 (10.6)**	-32.4%	31.1 (10.2)	18.8 (7.9)**	-39.5%
Vastus Lateralis	120.0 (41.0)	182.9 (65.1)**	52.4%	69.1 (24.5)	114.3 (40.7)**	65.0%	74.1 (45.2)	115.0 (39.6)**	55.2%	43.0 (24.6)	72.5 (24.9)**	68.6%
Vastus Medialis	116.6 (33.0)	192.2 (55.1)**	64.8%	76.4 (51.3)	133.4 (67.0)**	74.1%	83.5 (80.2)	136.0 (61.5)**	62.9%	43.4 (36.7)	81.5 (36.0)**	87.8%
Soleus	189.1 (141.4)	196.1 (82.5)	3.7%	92.3 (54.2)	110.5 (28.3)	19.2%	123.0 (71.4)	156.3 (64.7)	26.8%	54.3 (34.4)	77.7 (33.8)	43.1%

EMG- electromyography; MVIC- maximal voluntary isometric contraction; IMTP - isometric mid-thigh pull; ISQ - isometric squat;

Uni- unilateral; BI - bilateral

*<0.05 significant difference from IMTP

**<0.01 significant difference from IMTP