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The relationship between isometric mid-thigh pull force-time characteristics and swing performance in high-level youth golfers

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The production of vertical ground reaction force has been suggested to relate directly to club head speed (CHS) in golfers, providing a rationale for the implementation of strength and conditioning to enhance performance. The aim of the study was to determine the relationship between isometric mid-thigh pull (IMTP) force-time characteristics and measures of swing performance (CHS and Carry) in high-level youth golfers. Thirteen high-level youth golfers selected for their National Squad performed IMTP and swing testing using a TrackMan launch monitor across two testing sessions. Results revealed significant correlations between IMTP Peak Force (PF) and 6-iron Carry ($r=0.91$, $p<0.001$), Driver Carry ($r=0.91$, $p<0.001$), 6-iron CHS ($r=0.89$, $p<0.001$) and Driver CHS ($r=0.88$, $p<0.001$). All other variables showed trivial to large non-significant correlations. Findings support the use of the IMTP as a testing tool in high-level youth golfers and emphasise the importance of strength training within this population.

INTRODUCTION

The integration of biomechanical research into applied golf has allowed practitioners to obtain a wealth of information regarding kinetic and kinematic factors of the golf swing (Nesbit & Serrano, 2005). Hence, opportunities to discover limiting factors of performance and design appropriate interventions are becoming increasingly available. Whilst successful golf performance is multifaceted, the ability to maximise displacement of the ball through optimal swing performance has been shown to significantly correlate with a lower handicap (Betzler, Monk, Wallace, & Otto, 2012; Fradkin, Sherman, & Finch, 2004). This performance outcome is dependent upon linear velocity of the club head at impact with the ball, influenced by both the length of the arm-club system (ACS) and the angular velocity of the club head (Hume, Keogh, & Reid, 2005).

Whilst ACS length is dependent upon a combination of anthropometric and technical factors, angular velocity of the club head may be enhanced by utilising an efficient 'ground up' force transfer (Nesbit & Serrano, 2005). Utilising vertical ground reaction force (vGRF) creates a proximal to distal kinetic chain, in which angular velocity summates at each subsequent joint

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to transfer kinetic energy to the club head (Hellström, 2009). In conjunction with X-Factor, defined as the magnitude of separation between the pelvis and thorax (McLean, 1992), this 'temporal kinetic sequencing' is believed to be a key component of the modern golf swing. During the early downswing phase, further pelvis-torso separation known as X-Factor stretch (XFS) is believed to create a greater increase in angular velocity at distal segments of the body and a subsequent increase in CHS (Hellström, 2009). Findings from Queen, Butler, Dai, and Barnes (2013) demonstrated that lower handicap golfers may be capable of producing a greater vGRF at an earlier stage of the downswing, which appears to be supported by EMG analysis of lower body musculature (McHardy & Pollard, 2005). These kinetic factors appear consistent in both full and partial swings across a range of clubs (Tinmark, Hellström, Halvorsen, & Thorstensson, 2010), providing a clear mechanical model in which club head speed (CHS) can be maximised to improve golf performance.

The potential of resistance training to influence lower limb force production has led to the growth of strength and conditioning practices aimed at improving CHS. To date, most research has investigated the relationship between CHS and lower body strength diagnostics, with significant correlations reported using the counter-movement jump (CMJ, r = 0.44 – 0.79, Hellström, 2008; Read, Lloyd, Croix, & Oliver, 2013; Wells, Elmi, & Thomas, 2009; Wells, Mitchell, Charalambous, & Fletcher, 2018), squat jump (SJ, r = 0.45 – 0.82, Hellström, 2008; Lewis, Ward, Bishop, Maloney, & Turner, 2016; Read et al., 2013; Wells et al., 2018), drop jump (r = 0.56, Wells et al., 2018), 1 repetition maximum squat (r = 0.54, Hellström, 2008), and isometric mid-thigh pull (IMTP, r = 0.34 – 0.48, Wells et al., 2018) in professional and category 1 adult golfers ($p < 0.05$).

Recent research has suggested that the ability to maximise rate of force development (RFD) may also be relevant to swing performance (Read & Lloyd, 2014), as reported times of 280-290 ms between the start of the downswing and ball impact have been reported in PGA Tour golfers (McTeigue, Lamb, Mottram, & Pirozzolo, 1994). However, whilst this short time frame would support the importance of RFD for swing performance, the author's use of maximal upper body rotation as the determinant of downswing initiation may underestimate the duration of force production from the lower body. Furthermore, an average downswing time of 380 ms was reported for amateur players, suggesting that differences in playing ability may influence the relevance of specific force-time characteristics. It is yet to be explored whether this relationship between RFD and CHS is further influenced by age and maturation.

Isometric testing may provide a practical and time efficient measure of both maximal strength and RFD (Suchomel, Nimphius, & Stone, 2016), with an application to screening, talent development and the monitoring of strength and conditioning programmes. Recent findings have suggested that RFD from

0-150 ms and 0-200 ms, measured using an IMTP protocol, may correlate with CHS in highly skilled golfers ($r = 0.34 - 0.4$, $p < 0.05$, Wells et al., 2018). Similarly, RFD from 0-150 ms has demonstrated moderate correlations with peak CHS in recreational golfers when allometrically scaled for body mass ($r = 0.47$, $p = 0.06$, Leary et al., 2012). In support of these findings, IMTP testing has previously been used in athletic populations to demonstrate a relationship between isometric force-time characteristics and dynamic performance, including jumping (Nuzzo, McBride, Cormie, & McCaulley, 2008; West et al., 2011) and sprinting (West et al., 2011). However, literature investigating the relationship between IMTP force-time characteristics and golf swing performance is limited, and at present has only been conducted using elite adult, category 1 and recreational golfers (Leary et al., 2012; J. E. T. Wells et al., 2019, 2018).

Previous research investigating the relationship between physical characteristics and youth golf performance has identified that movement competency (Gould, Oliver, Lloyd, Neil, & Bull, 2018) and concentric power (Coughlan, Taylor, Jackson, Ward, & Beardsley, 2020) are strongly related to measures of swing performance. Coughlan et al. (2020) reported significant correlations between CHS and measures of physical performance in male and female youth golfers, including CMJ power ($r = 0.41 - 0.60$), seated medicine ball throw to the left ($r = 0.35 - 0.67$), rotational medicine ball throw to the left ($r = 0.57 - 0.71$) and rotational medicine ball throw to the right ($r = 0.56 - 0.62$, $p < 0.05$). In addition, only male youth golfers displayed a significant correlation between CHS and seated medicine ball throw to the right ($r = 0.61$, $p < 0.01$). Whilst these findings provide a rationale for field-based testing within youth golf, identifying how specific force-time characteristics relate to swing performance will further aid in the design and implementation of strength and conditioning programmes for this population. The aim of the current study was therefore to determine the relationship between isometric force-time characteristics and swing performance in high-level youth golfers.

METHODS

EXPERIMENTAL APPROACH TO THE PROBLEM

A cross-sectional correlation study design was used to determine the relationship between IMTP force-time characteristics and swing performance using both a 6-iron and driver golf club. IMTP force-time characteristics included measures of Peak Force (PF) and Force at 50, 100, 150, 200 and 250 ms, selected to replicate the reported duration of the downswing in golf (Cochran & Stobbs, 1996; McTeigue et al., 1994). Peak RFD and RFD during 0-50, 0-100, 0-150, 0-200 and 0-250 ms were selected based upon golf specific time frames and previous reliability studies of the IMTP (Haff, Ruben, Lider, Twine, & Cormie, 2015). CHS and Carry, representative of the angular velocity at the most distal part of the ACS and ball displacement following impact, were selected as swing performance variables. Ball displacement was defined as the total distance travelled whilst airborne, discounting the distance achieved through bounce and roll of the golf ball.

Data collection took place across two testing sessions, seven days apart, in which subjects performed their regular golf practice. Consent, subject characteristics and IMTP data were collected during session 1, with measures of swing performance collected during session 2. Testing sessions 1 and 2 were integrated into National Squad training camps completed at the beginning of the pre-season period, limiting the effects of golf training on testing results.

SUBJECTS

Thirteen high-level youth golfers (males: 7, females: 6; age: 15.6 ± 1.5 years; stature: 170.3 ± 6.8 cm; mass: 66.9 ± 13.6 kg) were recruited from a cohort of 61 National Development Squad players, of which 46 players met the inclusion criteria of the present study. Subjects were all aged 18 or under and had been identified as talented within their respective age groups nationally (handicap: 2.7 ± 3.0, range: +0.5 - 8). All participants had been competing in golf for a minimum of 3 years, engaging in strength and conditioning for an average of 2.5 years (range: 0 – 5) and had no prior experience of IMTP testing. Parental consent, participant assent and physical activity readiness questionnaires (PAR-Q) were obtained prior to testing for all participants under the age of 18. Informed consent and PAR-Q were obtained prior to testing for subjects aged 18 at the time of testing. All participants were informed of the benefits and risks associated with the testing procedure, with those declaring injuries or health issues withdrawn from the study. Ethical approval was granted by Cardiff Metropolitan University Research Ethics Committee in agreement with the Declaration of Helsinki.

PROCEDURES

Isometric Mid-Thigh Pull. Descriptive data was collected in session 1 following an initial explanation of the testing procedure. Mass and stature were measured using a portable stadiometer (SECA 321, Vogel & Halke, Hamburg, Germany) and digital scales (SECA 770, Vogel & Halke, Hamburg, Germany) to the nearest 0.1cm and 0.1kg, respectively. Prior to testing, participants conducted a ten-minute standardised warm up consisting of upper and lower body mobilisation exercises, rotational dynamic stretches, glute activation and plyometric jumps.

All IMTP testing was performed using a custom build IMTP rig positioned over dual force platforms (Kistler, 9287CA, Winterthur, Switzerland). A demonstration was provided by the experimenter, with the set up corresponding to that reported in previous research (Moeskops et al., 2018). Individualised pull positions were set for each subject by adjusting the bar height in 1cm increments until the subject was deemed to be in the correct pulling position, with the bar corresponding to the mid-point of the anterior thigh and appropriate flexion at the knee and hip. Knee and hip angles were not recorded, as previous research has suggested that a decrease in familiarisation time and learning effects may occur when using a self-determined set up position (Comfort, Jones, McMahon, & Newton, 2015). Subject's hands were strapped to the bar by the investigator using commercial lifting straps, before two submaximal warm up pulls were performed. Force plates were zeroed prior to each trial with the subject stood behind the force plate and strapped to the bar. For each trial, participants were requested to take minimal slack out of the bar and remain stable as the data acquisition was initiated. A countdown of '3, 2, 1, Pull' was given, with subjects pulling maximally for 5 seconds. Instructions were provided to pull as hard and as fast as possible (Haff et al., 2015), with strong verbal encouragement provided throughout testing. Each subject performed two trials separated by a rest period of 90 seconds.

Assessment of IMPT Force-Time Characteristics. Force platform output sampling at a rate of 1000 Hz was recorded for a total of 10 seconds and further analysed using computer software (BioWare V5.3.0.7, Kistler, Winterthur, Switzerland). Data for vGRF was further filtered at 100 Hz to reduce noise and exported to a custom-built spreadsheet (Excel 2016, Microsoft, Washington, United States). For each trial, vGRF from each force platform was combined to give total instantaneous vGRF at 1 ms intervals. PF (N) was provided as a net value, calculated as the highest vGRF minus the subject's body mass. To ensure that each effort was maximal, subjects with a difference of >250 N in PF values between trials were removed post testing as the option to perform additional trials was not possible (Leary et al., 2012). Force at 50, 100, 150, 200 and 250 ms were calculated as the vGRF at each specific time point following the onset of the pull, minus the subject's body mass. The onset of the pull was defined as the time at which instantaneous RFD (change in force at each millisecond interval) exceeded 5 standard deviations of the baseline, as used in previous IMTP research (Dos'Santos, Jones, Comfort, & Thomas, 2017). This baseline was calculated as the average RFD during the first second of data collection, in which the participants had been instructed to remain stable in the set-up position. Peak RFD ($N.s^{-1}$) was calculated as the highest change in force over 20 ms time intervals, as this has been suggested to provide the most reliable measure of Peak RFD (Haff et al., 2015). RFD time zone bands were selected based upon previous research (Haff et al., 2015; Leary et al., 2012; J. E. T. Wells et al., 2018) and calculated as the change in force during 0-50, 0-100, 0-150, 0-200 and 0-250 ms intervals. All variables were tested for reliability by logarithmical transformation using a custom spreadsheet (Hopkins, 2017). Only IMTP PF (ICC = 0.95, CV = 6.8%) was deemed reliable based upon previous guidelines (ICC > 0.80, CV < 10%; Brady, Harrison, & Comyns, 2018). For all IMTP variables, the peak value reported across the two trials was used for further statistical analysis.

Swing Performance. Swing performance testing was conducted by golfers hitting 5 shots with a 6-iron and driver, seven days following the IMTP data collection. Participants performed a standardised warm up followed by self-selected practice swings prior to testing (J. E. T. Wells et al., 2018). Data collection consisted of subjects performing 5 shots with each club selection, with 30 seconds of rest in between trials. Shots were aimed at specific targets on a driving range and performed using standardised range balls, with each participant using their own clubs. Measures were recorded using TrackMan radar technology (TrackMan 3e, Vedbaek, Denmark) set up according to manufacturer details, as used in previous studies (Coughlan et al., 2020; J. E. T. Wells et al., 2018). All TrackMan data was collected by the same professional golf coach who had been accredited by the Professional Golfers' Association (PGA).

Assessment of Swing Performance Data. Data was displayed in TrackMan Performance Studio software (TrackMan, Vedbaek, Denmark), with CHS and Carry further analysed for the 6-iron and driver. Measures were initially recorded in miles per hour (mph) and yards (y), respectively, and subsequently converted to meters per second ($m.s^{-1}$) and meters (m) prior to analysis. All measures were deemed reliable (ICC = 0.86 - 1.00, CV = 0.8 - 6.9%) as assessed by logarithmical transformation in a custom spreadsheet (Hopkins, 2017). The peak CHS and Carry recorded for each club across five trials were used for further statistical analysis.

STATISTICAL ANALYSES

All measures were reported as median and interquartile ranges. Data was assessed for normality using a Shapiro-Wilk test and a calculation of Z Scores for skewness and kurtosis. A bivariate correlation was performed to investigate the relationship between IMTP and swing performance variables, with the distribution of data dictating whether a Pearson or Spearman rank-order correlation was selected to test each variable. Assessment of Z scores and Shapiro-Wilk's test revealed data for Driver Carry, Force at 200 ms, Force at 250 ms, Peak RFD, RFD 0-200 ms and RFD 0-250 ms violated the assumptions of normality. Subsequently, these variables underwent non-parametric testing using a Spearman rank-order correlation. All other variables for IMTP and swing performance met the assumptions of normality, and a Pearson correlation coefficient was performed. An alpha level of $p = 0.05$ was selected for all statistical tests. Based upon previous research, correlations were reported as either trivial ($r = 0.0 - 0.09$), small ($r = 0.1 - 0.29$), moderate ($r = 0.3 - 0.49$), large ($r = 0.5 - 0.69$), very large ($r = 0.7 - 0.89$) or nearly perfect ($r \geqslant 0.9$) (Hopkins, Marshall, Batterham, & Hanin, 2009). Statistical analysis was performed using SPSS (Version 24.0, IBM, Armonk, New York).

RESULTS

Median values and interquartile ranges for IMTP force-time characteristics and swing performance variables are presented in Table 1.

Table 1. Median and interquartile ranges for swing performance and IMTP measures

Measure	Median	Interquartile Range
CHS 6 Iron ($m.s^{-1}$)	34.7	32.3 – 41.4
CHS Driver ($m.s^{-1}$)	40.5	39.0 – 48.0
Carry 6 Iron (m)	147.2	133.7 – 169.8
Carry Driver (m)	183.5	170.1 – 234.3
Peak Force (N)	1399.2	1145.9 – 1735.4
Force at 50ms (N)	251.3	191.4 – 312.2
Force at 100ms (N)	452.1	340.3 – 566.1
Force at 150ms (N)	603.3	517.2 – 945.8
Force at 200ms (N)	862.2	706.8 – 1044.1
Force at 250ms (N)	933.2	890.3 – 1072.7
Peak RFD ($N.s^{-1}$)	7477.3	5890.0 – 9803.7
RFD 0-50ms ($N.s^{-1}$)	4014.6	2603.4 – 5867.8
RFD 0-100ms ($N.s^{-1}$)	3809.5	2649.1 – 5589.5
RFD 0-150ms ($N.s^{-1}$)	3776.8	2917.9 – 5595.0
RFD 0-200ms ($N.s^{-1}$)	4172.0	3407.6 – 4724.4
RFD 0-250ms ($N.s^{-1}$)	3584.9	3198.8 – 4241.5

Correlational analysis revealed multiple significant positive correlations between IMTP force-time characteristics and swing performance (Table 2). Nearly perfect significant positive correlations were shown between IMTP PF and Carry using a 6-iron ($r = 0.91$, $p < 0.001$, n = 13) and Driver ($r = 0.91$, $p < 0.001$, n = 13). Similarly, very large significant positive correlations were found between PF and CHS with both a 6-iron ($r = 0.89$, $p < 0.001$, n = 13) and Driver ($r = 0.88$, $p < 0.001$, n = 13). Large correlations were reported between Force at 250 ms and 6-iron Carry ($r = 0.55$, $p = 0.05$, n = 13) and CHS ($r = 0.5$, $p = 0.08$, n = 13); RFD 0-250 ms and 6-iron Carry ($r = 0.52$, $p = 0.07$, n = 13), CHS ($r = 0.51$, $p = 0.07$, n = 13), and Driver CHS ($r = 0.51$, $p = 0.07$, n = 13), although results were not statistically significant. Additionally, a large non-significant negative correlation was reported between RFD 0-100 ms and Driver CHS ($r = -0.5$, $p = 0.08$, n = 13). Trivial to moderate non-significant correlations were reported between all other IMTP and swing performance variables.

DISCUSSION

The results of the present study support a relationship between specific IMTP force-time characteristics and swing performance in high-level youth golfers, building upon the current body of evidence within this population. Findings support the importance of maximal lower body force production in swing performance, revealing significant correlations between IMTP PF and both CHS and Carry. However, no further significant correlations were reported between force-time characteristics and swing performance. CHS and Carry displayed similar relationships with force-time characteristics, whilst relationships also appeared consistent for both the 6-iron and Driver.

Table 2. The relationship between IMTP and swing performance using a 6 Iron and Driver

	CHS 6-iron		CHS Driver		Carry 6-iron		Carry Driver	
IMTP Force-Time Characteristic	*r value*	*Sig (p)*	*r value*	*Sig (p)*	*r value*	*Sig (p)*	*r value*	*Sig (p)*
Peak Force (N)	.89	<.001*	.88	<.001*	.91	<.001*	.91	<.001*
Force at 50ms (N)	-.12	.69	-.20	.52	.001	1.0	-.20	.51
Force at 100ms (N)	-.37	.22	-.41	.16	-.20	.52	-.39	.19
Force at 150ms (N)	.02	.94	-.02	.95	.21	.49	-.07	.83
Force at 200ms (N)	.42	.16	.37	.21	.48	.09	.26	.40
Force at 250ms (N)	.50	.08	.50	.08	.55	.05	.43	.14
Peak RFD ($N.s^{-1}$)	.34	.25	.35	.24	.39	.22	.37	.22
RFD 0-50ms ($N.s^{-1}$)	-.24	.44	-.32	.28	-.14	.65	-.20	.52
RFD 0-100ms ($N.s^{-1}$)	-.45	.12	-.50	.08	-.28	.35	-.46	.12
RFD 0-150ms ($N.s^{-1}$)	.01	.97	-.04	.90	.21	.50	-.04	.90
RFD 0-200ms ($N.s^{-1}$)	.31	.30	.28	.35	.35	.24	.24	.44
RFD 0-250ms ($N.s^{-1}$)	.51	.07	.51	.07	.52	.07	.46	.12

* denotes a significant relationship (p<0.05)

The ability to produce high levels of force during the downswing has been suggested to be a critical factor in determining CHS (Nesbit & Serrano, 2005). It is plausible that a golfer capable of producing a large IMTP PF may exhibit considerable vGRF outputs during the downswing, increasing the angular velocity of the ACS and ultimately CHS. The current findings, supporting a relationship between IMTP PF and CHS in high-level youth golfers, are in agreement with those previously reported within adult male golfers (J. E. T. Wells et al., 2018). Despite similar handicaps, high-level youth golfers demonstrated a lower mean Driver CHS (42.5 ± 4.8 vs. 49.41 ± 2.46 $m.s^{-1}$) and IMTP PF (1457.2 ± 356.3 vs. 1604.57 ± 391.47 N), yet a stronger correlation between the two variables in comparison with adult golfers ($r = 0.88$ vs. 0.48, $p < 0.01$). The difference in PF characteristics between youth an adult population may be explained by the changes in body composition and strength associated with growth and maturation (Radnor et al., 2018). Although the long-term effect of strength training and maturation on CHS have yet to be investigated within this population, the strength of the correlation between PF and CHS would appear to support the importance of developing maximal strength in youth golfers. In contrast with elite adult populations, research into recreational golfers has demonstrated no significant correlation between IMTP PF and CHS ($r = 0.20$, $p > 0.05$, Leary et al., 2012). The extent to which

PF relates to swing performance may therefore be influenced by both playing ability and biological age. The ability to transfer vGRF through the kinetic chain into the club head is defined as the 'efficiency' of a golf swing (Nesbit & Serrano, 2005), and may offer a rationale for the difference in relationship between elite and recreational golfers. Whilst the importance of strength training for youth golfers appears clear, it is possible that technical proficiency may moderate the degree to which peak force influences swing performance.

Further findings by Wells et al. (2018) demonstrate a trend towards large correlations as IMTP force-time characteristics approach 250 ms, with IMTP RFD 0-150 ($r = 0.34$, $p < 0.05$) and 0-200 ms ($r = 0.4$, $p < 0.05$) showing significant correlations with CHS. These findings support the theory that a greater CHS may be related to the ability to maximise force in under 250 ms. One explanation for this may be the ability to express force in the time associated with the top of the backswing to ball impact, reported to be between 230 ms (Cochran & Stobbs, 1996) and 290 ms (McTeigue et al., 1994). Within this downswing it has been suggested that the acceleration phase, defined as the period between the club reaching horizontal during the late downswing phase and ball impact, involves the greatest level of muscle activity (McHardy & Pollard, 2005). This has been supported by Nesbit and Serrano (2005), who suggested that high-level golfers may initially work at a slower rate during the downswing, before maximising club velocity towards ball impact. Indeed, a lower velocity during the early downswing has been attributed to increasing the time over which force can be applied, thus increasing the overall impulse of the downswing (Read et al., 2013). Although findings were non-significant, Force at 250 ms and RFD 0-250 ms displayed the largest correlations with CHS and Carry amongst time dependent variables within the current study ($r = 0.43 - 0.55$, $p > 0.05$). Furthermore, a non-significant negative trend was observed between measures of swing performance and force-time characteristics up to 100 ms ($r = 0.001 - -0.5$, $p > 0.05$). Whilst definitive conclusions cannot be inferred from these findings, the trends observed provide a rationale for future research into force-time characteristics within this population. Taken in the context of previous findings (J. E. T. Wells et al., 2018), it is possible that the ability to produce high levels of force during early stages of the IMTP (under 100 ms) may not relate to increased CHS and Carry, supporting previous dismissals of the importance of early RFD in the golf swing.

The relationship between IMTP force-time characteristics and measures of swing performance may be explained by the similarity in underlying force production properties. Due to the time frame associated with the downswing, it has been suggested that the golf swing may represent a slow stretch shortening cycle (SSC) activity in which contractile elements are responsible for force production (J. E. T. Wells et al., 2018). This theory appears to be supported by CMJ testing, classified as a slow SSC activity, which has demonstrated significant correlations with CHS in both youth (Coughlan et al., 2020) and adult golfers (Hellström, 2008; Lewis et al., 2016; J. E. T. Wells et al., 2018). Findings from the present study suggest that contractile peak force production, as assessed using an IMTP protocol, is highly related to swing performance in youth golfers and adds to the current body of literature investigating the physical characteristics of golfers. This evidence may provide direction for strength and conditioning practitioners, suggesting that training aimed at improving peak force and slow SSC capabilities may be important in the development of youth golfers. Future research should aim to utilise isometric testing, jump testing and testing in the transverse plane within an elite youth population, in order to further investigate the relationship between force-time characteristics and swing performance. Similarly, studies should aim to identify if longitudinal changes in IMTP PF and RFD following strength training correlate to changes in CHS and carry in youth golfers.

LIMITATIONS

Although the present study provides novel findings regarding the relationship between lower body force-time characteristics and swing performance in youth golfers, considerations for the methods should be made when comparing findings to previous research. Notably, a larger sample size may have been required to find statistically significant relationships to support the trends reported. Due to the small sample size and large CV's reported, findings relating to time dependent measures of force production should not be generalised beyond the findings of this study. Despite this, they may provide a rationale for future research to be conducted using a large sample of elite youth golfers. Similarly, the present study did not aim to investigate the influence sex or maturation on force-time characteristics and swing performance. An understanding of how these factors relate to physical characteristics will further support strength and conditioning practitioners in the design of specific youth golf programmes.

Thirdly, due to the time constraints of integrating testing into a high-performance squad setting, familiarisation of the IMTP prior to testing was not possible. Although the CV's reported for IMTP variables were similar to those reported in other youth populations (Moeskops et al., 2018), it is possible that a familiarisation session implemented 48 hours prior to testing may have improved the reliability of the findings (Comfort et al., 2019).

Finally, it should be considered that the ability to produce high levels of vGRF is only one component of the downswing (Hume et al., 2005) and that factors such as XFS may influence the relationship with force-time characteristics (Hellström, 2009). Future research should aim to determine the relationship between isometric force-time characteristics and joint segment kinematics to identify the role of vGRF on pelvis rotation, XFS and swing performance.

CONCLUSION

The present study provides support for the use of maximal isometric testing in high-level youth golfers, with positive implications for both testing and monitoring development athletes. IMTP PF was deemed reliable and demonstrated the largest correlation with measures of swing performance, whilst Force and RFD produced within a time frame similar to that of the downswing (200-250 ms) showed non-significant positive trends. To the author's knowledge, these are novel findings within a high-level youth population and add to the current evidence supporting a relationship between lower body peak force production and swing performance. Due to the low reliability associated with time dependent IMTP measures and a lack of significant findings, consideration should be given when attempting to infer the role of RFD on swing performance.

PRACTICAL APPLICATION

The IMTP, in addition to jump testing, may provide useful lower body kinetic data to test and monitor youth golfers. Through studying the relationship between CHS and both the magnitude and rate of force development, practitioners may be able to implement training interventions to target golf specific qualities of the force-velocity curve. The current findings, in conjunction with previous literature, suggest that resistance training protocols for youth golfers should aim to improve vertical PF production and slow SSC capabilities. This could be achieved using lower body compound exercises in the sagittal plane such as squats, deadlifts, jumps, and lunges. A mobility based warm up and exercises in the transverse plane, such as cable chops and rotational throws, could be included to form a balanced strength and conditioning programme for the youth golfer. The low CV's associated with IMTP PF warrant its use as a monitoring tool and would allow meaningful changes in PF to be determined following a strength and conditioning programme.

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