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Abstract

A number of field-based investigations have evidenced practically significant relationships between clubhead velocity (CHV), vertical jump performance and maximum strength. Unfortunately, whilst these investigations provide a great deal of external validity, they are unable to ascertain vertical ground reaction force (vGRF) variables that may relate to golfers' CHVs. This investigation aimed to assess if the variance in European Challenge Tour golfers' CHVs could be predicted by countermovement jump (CMJ) positive impulse (PI), isometric mid-thigh pull (IMTP) peak force (PF) and rate of force development (RFD) from 0-50 ms, 0-100 ms, 0-150 ms and 0-200 ms. Thirty-one elite level European Challenge Tour golfers performed a CMJ and IMTP on dual force plates at a tournament venue, with CHV measured on a driving range. Hierarchical multiple regression results indicated that the variance in CHV was significantly predicted by all four models (model one $R^2$ = 0.379; model two $R^2$ = 0.392, model three $R^2$ = 0.422, model four $R^2$ = 0.480), with Akaike's information criterion indicating that model one was the best fit. Individual standardised beta coefficients revealed that CMJ PI was the only significant variable, accounting for 37.9% of the variance in European Challenge Tour Golfers' CHVs.

Key words: Golf, Impulse, Peak Force, Rate of Force Development.

## Introduction

The ability of professional golfers to drive a ball over greater distances is associated with statistically significant lower scores on Par-4 and Par-5 holes (Hellström, Nilsson & Isberg, 2014). While a number of impact factors combine to determine the resultant ball flight, drive distance is most influenced by clubhead velocity (CHV) at the moment of impact (Hume, Keogh & Reid, 2005). Golfers can increase their CHV through technical changes in their swing and utilising appropriately fitted equipment (Cochran & Stobbs, 1999). A greater number of golfers, however, including European Challenge Tour players, are engaging in strength and conditioning (S&C) due to a growing body of evidence indicating improvements in CHV, ball velocity and drive distance following resistance training (Fletcher & Hartwell, 2004; Doan, Newton, Kwon & Kraemer, 2006, Driggers & Sato, 2017). In addition to these findings, a number of high profile players have openly advocated the positive impact resistance training has had on their game.

A number of field-based investigations have shown practically significant relationships between CHV and both vertical jump (peak power and jump height) performance ($r$ = 0.54: Read, Lloyd, De Ste Croix & Oliver, 2013; $r$ = 0.61: Hellström, 2008; $r$ = 0.82 Lewis, Ward, Bishop, Maloney & Turner, 2016) and repetition maximum (RM) strength during a back squat ($r$ = 0.54: Hellström, 2008; $r$ = 0.81: Parchmann & McBride, 2011). As such, these protocols provide an opportunity to physically profile and monitor golfers during a tournament season. Whilst these field-based procedures offer a great deal of accessibility, without laboratory equipment such as force plates, there is ultimately limited extractable biomechanical data to analyse and guide future training interventions. In addition, performing a RM test to failure may deter golfers from engaging in this assessment protocol during a tournament season. Over recent years, however, the use of an isometric mid-thigh pull (IMTP) has been validated as an alternative to RM testing (Haff, Ruben, Lider, Twine & Cormie, 2015). Not only does this procedure offer a safer alternative (De Witt et al., 2018), it also allows the assessment of a number of vertical ground reaction force (vGRF) variables such as peak force (PF) and rate of force development (RFD).

The interface between the ground and the golfer has been cited as an important interaction during the swing (Hume et al., 2005; Lynn & Wu, 2017). Indeed, research has evidenced that the downswing of highly skilled golfers was initiated from the ground-up (Nesbit & Serrano, 2005), with the energy transferred through the body's kinetic chain, which, ideally will reach the clubhead at the moment of impact. This has led to a number of speculative suggestions that vGRF variables such as PF (Doan et al., 2006), RFD (Read & Lloyd, 2014; Hellström, 2017), and impulse (Myers et al., 2008) may hold important relationships with CHV.

Due to the practically significant relationships between CHV and 1-RM back squat strength (Hellström, 2008; Parchmann & McBride, 2011), it appears plausible that PF may also hold these significant relationships with golfers CHV. The duration of the downswing however, has been referenced to last from 230-284 ms (Cochran & Stobbs, 1999; Tinmark, Hellström, Halvorsen & Thorstensson, 2010). Since it can take up to 900 ms to achieve PF (Blazevich, 2011), this has led authors to suggest that there is not enough time available to achieve maximum force and that RFD is a more important mechanism for generating CHV (Read & Lloyd, 2014; Hellström, 2017). Impulse (force x time) is directly proportional to the change in momentum (mass x velocity). Since a golfer's mass will remain constant between shots, increasing the force or the duration that force acts over may directly increase CHV. McTeigue, Lamb, Mottram and Pirozzolo (1994) evidenced that as highly skilled golfers transition at the top of the backswing, the lower body begins to apply force to the ground whilst the upper body continues to rotate away from the target. Consequently, it is reasonable to suggest that elite golfers may be able to increase impulse (assuming no reduction in mean force) by utilising a sequence working from the ground-up, or by lengthening their backswing, subsequently increasing the duration of the downswing. While there would appear to be a ‘theoretically ideal’ proximal to distal kinematic sequencing pattern (e.g. order of peak angular velocity = pelvis, torso, arms, clubhead) during the downswing, research has shown that only 25% of PGA Tour players tested adopted this sequence (Cheetham & Broker, 2016). Although highly skilled golfers may adopt a different kinematic sequence to deliver the club to the ball in an effective manner, it is widely accepted that the transition from the backswing to the downswing is initiated from the ground-up (Nesbit & Serrano, 2005). These ground reaction forces act in opposite directions to create a force couple which facilitate rotation during the downswing (Hellström, 2009). Indeed, research has indicated that highly skilled golfers are able to produce ground reaction forces earlier in the downswing (Barretine, Fleisig & Johnson, 1994) and with a greater magnitude when compared to lower skilled golfers (Lynn, Noffal, Wu, & Vandervoort, 2012), which, would theoretically increase the impulse they produce.

There is very little research, however, that has attempted to quantify the use of vGRF variables to predict CHV. Of note, a recent investigation utilising force plates, revealed practically significant relationships between CHV and countermovement jump (CMJ) positive impulse (PI) ($r = 0.788$, $p<0.001$) and IMTP PF ($r = 0.482$, $p<0.01$) in highly skilled golfers (handicap: <5 strokes) (Wells, Mitchell, Charalambous & Fletcher, 2018). However, the laboratory-based nature of the design, limits the accessibility of such equipment during a tournament season. Further still, laboratory testing is not representative of a tournament practice setting encountered by an elite level golfer. Over recent years, advances in technology have led to the development of cost effective and portable force plates, thus making such analysis more accessible to sports scientists and golfers. Consequently, the aim of this investigation was to assess if the variance in CHV could be explained by CMJ PI, IMTP PF, RFD from 0-50 ms, 0-100 ms, 0-150 ms and 0-200 ms in European Challenge Tour golfers. It was hypothesised that

CMJ PI, IMTP PF, and RFD from 0-50 ms, 0-100 ms, 0-150 ms and 0-200 ms would be able to significantly predict the variance in CHV.

## Methods

### *Participants*

A cross-sectional design was employed for this investigation. Thirty-one right-handed male European Challenge Tour golfers (age: 26.9 ± 5.4 years, height: 1.8 ± 0.06 m, mass: 81.8 ± 12.2 kg) were recruited to participate in this investigation using convenience sampling. Players from the 2017 European Challenge Tour (an elite professional golf circuit with tournaments in Europe, Asia and Africa) season representing 13 different countries, volunteered to take part in this investigation. All participants were experienced golfers and, based on personal estimations, reported engaging in an average of 36.5 ± 8.9 hours of golf per week. Participants were injury free, completed a physical activity readiness questionnaire (PAR-Q) and provided informed consent to take part in the investigation. Ethical approval was granted by the University's Research Ethics committee.

### *Experimental trials*

*Assessment procedures:* Data collection was conducted at Luton Hoo Hotel which was the host venue for the European Challenge Tour event. All of the testing procedures (CHV, IMTP and CMJ) were performed on the same day with a 15-minute recovery separating the force plate and CHV testing, which were conducted using a counterbalanced design. As a standardised warm-up, participants performed a series of dynamic stretches including clock lunges, overhead squats, gluteal bridges, scapula wall slides, thoracic rotations, internal and external hip rotations and vertical and horizontal arm swings prior to performing the IMTP and CMJ (Wells et al., 2018). Both the IMTP and CMJ tests were performed on dual PASCO Scientific force plates (PASCO Scientific 2141, California, USA) sampling at 1000 Hz. Force plates were checked for concurrent validity against Kistler force plates (Kistler 9281, Kistler Instruments, Winterthur, Switzerland) prior to testing (CMJ PI: Kistler = 317.5 ± 7.4 N·s; PASCO Scientific = 316.5 ± 7.4 N·s, $r = 0.985$, $p<0.01$). Given that the hands were pulling a fixed resistance at a maximal effort during the IMTP, it was decided that this protocol should be performed prior to the CMJ in order to offer more time for recovery prior to CHV testing.

*Isometric mid-thigh pull:* All isometric testing was performed in a custom built portable rack. Prior to data collection, a standardised verbal explanation and demonstration was provided, followed by one sub-maximal trial performed by each participant. Participants were positioned into their individual second-pull position of the clean, since this has been shown to correspond to the portion of the clean that generates the highest force output (Garhammer, 1993). From this position knee (145 ± 7°) and hip (136 ± 11°) angles were recorded with a universal goniometer. Participants' hands were attached to the bar with lifting straps to enable maximal effort, without any limiting factors caused by the grip. Once the lifting position had been set, the participants took 'slack' out of the bar and remained motionless. Participants were instructed to pull the bar as hard and as fast as possible after a countdown of '3, 2, 1 pull', with maximal isometric effort applied for five seconds as recommended by Haff et al. (2015). Verbal encouragement was given throughout the effort. Following each maximal lift, participants sat on a chair, but remained strapped to the bar to maintain a constant hand position between trials. A total of two pulls were performed with three minutes recovery time between each (Wells et al., 2018). During this rest period, an experienced biomechanist visually inspected the force-time curve to assess if the participant had performed a countermovement prior to the maximal contraction. If a countermovement was observable, the test was performed again following the allocated rest interval.

*Countermovement Jumps:* All participants were taken through a standardised verbal explanation and demonstration by the investigator. Following this, participants performed two practice trials prior to completing the test procedures. Countermovement jumps started with the participants standing upright before lowering themselves into a self-selected squat depth and immediately jumping as high and as fast as possible on the command '3, 2, 1, jump'. A total of two trials were performed on the dual force plates, with the feet hip width apart and hands placed on the hips. Each trial was interspersed with a two-minute recovery period.

*Clubhead velocity assessment*: Clubhead velocity was measured using a TrackMan 3e launch monitor (Interactive Sports Games, Denmark), as used by Oliver, Horan, Evans and Keogh (2016). The TrackMan 3e measures CHV at the instantaneous moment prior to impact (TrackMan, 2018), with research showing a median difference of -0.49 m/s (lower and upper interquartile range 0.85 – 0 m/s) with an 87% chance of always being within 1.12 m/s of the gold standard measure (Leach, Forrester, Mears & Roberts, 2017). Clubhead velocity was measured at a driving range at the tournament venue. The TrackMan 3e was set-up based on manufacturer's guidelines with the investigator specifying the intended target line. Participants performed their own golf specific warm-up followed by a self-selected number of warm-up shots (3 ± 2 shots) hit with a driver. Participants used their own custom fit driver for data analysis. To ensure the methods remained representative of a tournament setting, participants were instructed to aim along the target line and to strike the ball with maximum effort, whilst maintaining their normal swing mechanics and a centred strike on the clubface. Maximum CHV, however, was tested to ensure that effort was standardised within and between participants. Participants self-selected and struck five new premium quality range balls, aiming down the target line and hit off a standardised wooden tee used during the tournament.

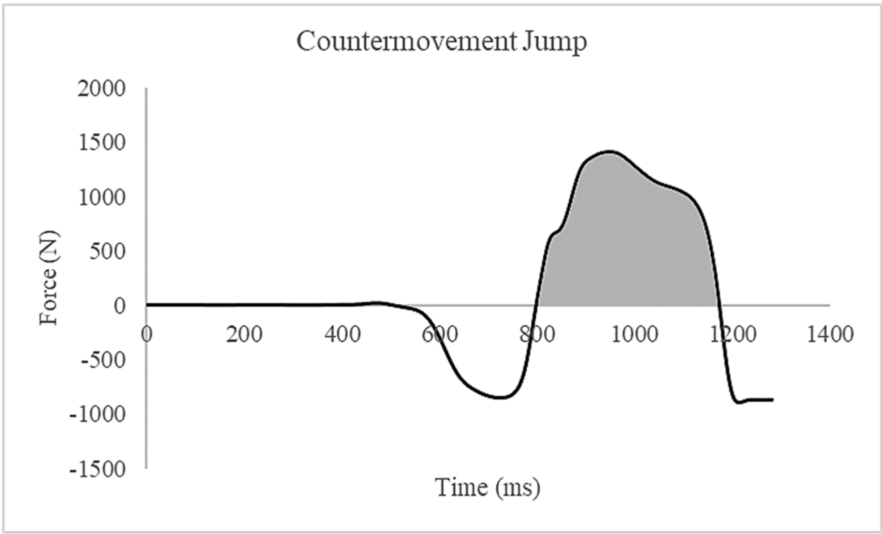
Centeredness of strike was determined by sound, feel and the ball flight, with the investigator confirming verbally with the participant after each shot. Any shots that fell outside these criteria were discarded and additional shots were performed, up to a maximum of ten shots.

### *Data analysis*

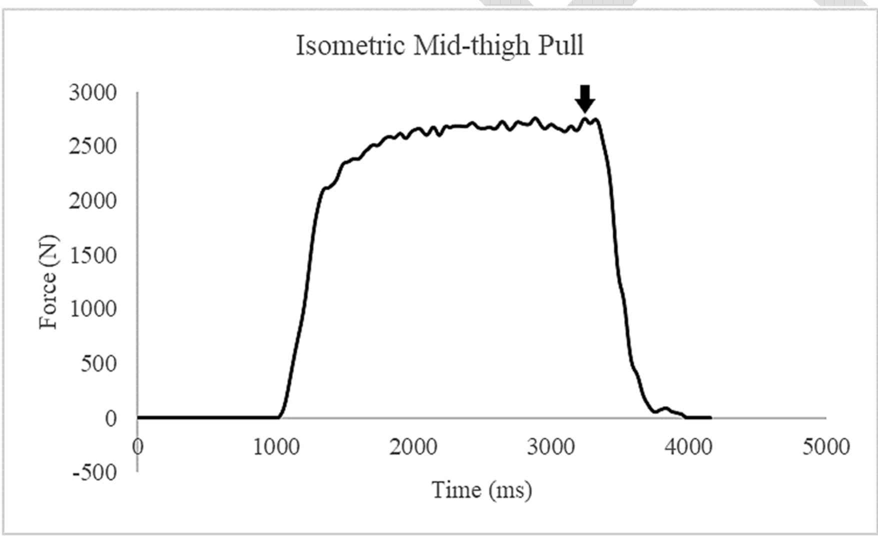
*Smoothing and residual analysis:* All data was smoothed with a low pass 4th order Butterworth filter as described by Winter (2009). Residual analysis was used to determine optimal cut-off frequency (Winter, 2009), which was 30 Hz for the IMTP and 100 Hz for the CMJ. Both residual analysis and smoothing was conducted using the biomechanics tool bar in Microsoft Excel. The instance of movement initiation was determined based on a 10 N vGRF threshold shift from baseline measurements as utilised by Tirosh & Sparrow (2003).

*Kinetic analysis*: Countermovement jump PI was calculated from the area underneath the force-time curve (this can be seen as the shaded area in Figure 1). This is calculated from the instantaneous moment where force first returns to bodyweight (which is the timepoint when peak negative velocity of the centre of mass is reached), up until the point that force returns back to zero and peak positive velocity of the centre of mass is achieved.

Peak force generated during the IMTP was established from the maximal vGRF on the force-time curve subtracted by the lowest starting force (Figure 2). Rate of force development was calculated as the change in force divided by the change in time over pre-determined time integrals of 0-50 ms, 0-100 ms, 0-150 ms and 0-200 ms. The peak data for each of these kinetic variables were taken forward for analysis, even if they occurred in separate trials (e.g. RFD and PF during the IMTP).




<u>Figure 1</u>: Force-time curve for a countermovement jump. The shaded grey area indicates the part of the curve used to calculate positive impulse.




<u>Figure 2</u>: Force-time curve data for an isometric mid-thigh pull. The arrow above the force-time curve represents the peak force generated.

*Clubhead velocity data:* The TrackMan 3e launch monitor provided real-time data on each participant's CHV for the five trials. From the five trials, the drive that generated the greatest CHV at impact was taken forward for analysis.

*Statistical analysis*

Within-session reliability was determined using the coefficient of variation (CV) statistic and respective 95% confidence intervals. For each variable, acceptable reliability was determined as a CV <15% (Haff et al., 2015). Data were analysed through multiple regression analysis using hierarchical entry, based on the previous findings of Wells et al., (2018), with CHV considered the criterion variable. Four models were generated to assess the use of the independent variables to predict variance in CHV. The assumption of independent errors was assessed through Durban-Watson test, with multicollinearity measured using variance inflation factors (VIF). The level of significance for all tests was set to $p<0.05$, with effect size measured using the $F^2$ statistic as suggested by Cohen (1988). This was calculated using the equation, $F^2 = R^2 / 1 - R^2$, and the size of the effect determined as >0.02 = small, >0.15 = moderate and >0.35 = large. Each model's fit was assessed using Akaike's information criterion (AIC).

Table 1: Descriptive statistics for each parameter, along with their respective within sessions coefficient of variation and 95% confidence intervals.

| | | | | 95% CI | |
|---|---|---|---|---|---|
| Parameter | Mean | SD | CV% | Lower | Upper |
| Peak CHV (m/s) | 52.45 | 2.75 | 0.79 | 0.67 | 0.90 |
| IMTP Peak Force (N) | 2093.31 | 365.97 | 3.44 | 2.43 | 4.44 |
| RFD 0-50 (N/s) | 7833.04 | 5530.74 | 23.55 | 17.79 | 29.31 |
| RFD 0-100 (N/s) | 6109.92 | 3073.52 | 30.36 | 22.52 | 38.21 |
| RFD 0-150 (N/s) | 5680.65 | 2466.21 | 12.54 | 8.94 | 16.14 |
| RFD 0-200 (N/s) | 6064.91 | 2123.18 | 10.52 | 7.12 | 13.92 |
| CMJ PI (N·s) | 279.81 | 46.85 | 1.71 | 1.21 | 2.21 |

## Results

High levels of reliability were observed for CHV (CV = 0.79%), IMTP PF (CV = 3.44%), CMJ PI (CV = 1.71%), and acceptable reliability for RFD from 0-150 ms (CV = 12.54%) and RFD from 0-200 ms (CV = 10.52%) (Table 1). Each of the other RFD time integrals were deemed unreliable since all CVs were greater than 15%. The assumption of independent errors and multicollinearity were both met through the Durban-Watson test and VIF (Table 2). Multiple regression analysis indicated that each of the four models were able to predict practically significant variations in CHV. For model one, CMJ PI was a large significant predictor of CHV ($R^2$ = 0.379, $p$<0.001, $F^2$ = 0.61) with $R^2$ increasing as each independent variable was added (Table 2). Table 2 provides the model parameters indicating the effect each variable had on CHV, when all other predictors were held constant. Individual AIC indicated that model one was the best fit for explaining the variance in CHV. Within each model, CMJ PI was the only variable that was able to predict a change in CHV and was considered to be a large effect size ($F^2$ = 0.61) in model one (Cohen, 1988). Post hoc analysis for model one indicated a statistical power of 0.99 when calculated from the effects size $F^2$ (0.61), alpha value (0.05) sample size (n = 31) and the number of predictors (1), which is greater than the 0.8 recommended minimum threshold (Field, 2014).

Table 2: Linear model for the predictors of CHV presenting the $R^2$, unstandardized beta coefficients (b) and their respective 95% confidence intervals, standard errors (SE B) the standardised beta ($\beta$) coefficients, and the variance inflation factor (VIF) for each predictor within the four models.

| | | | | 95% CI | | | | |
|---|---|---|---|---|---|---|---|---|
| Model | | $R^2$ | b | Lower | Upper | SE B | $\beta$ | VIF |
| 1 | Constant | 0.379** | 94.698 | 83.559 | 105.837 | 5.446 | | |
| | CMJ PI | | 0.081 | 0.042 | 0.120 | .019 | 0.616** | 1.000 |
| 2 | Constant | 0.392* | 91.955 | 78.590 | 105.32 | 6.525 | | |
| | CMJ PI | | 0.075 | 0.033 | 0.118 | 0.021 | 0.574* | 1.135 |
| | IMTP PF | | 0.002 | -0.003 | 0.007 | 0.003 | 0.122 | 1.135 |
| 3 | Constant | 0.422* | 91.056 | 77.664 | 104.448 | 6.527 | | |
| | CMJ PI | | 0.079 | 0.037 | 0.122 | 0.021 | 0.602* | 1.162 |
| | IMTP PF | | 0.004 | -0.002 | 0.010 | 0.003 | 0.220 | 1.460 |
| | RFD 0-200 | | -0.001 | -0.002 | 0.000 | 0.001 | -0.204 | 1.418 |
| 4 | Constant | 0.480* | 94.334 | 80.789 | 107.88 | 6.590 | | |
| | CMJ PI | | 0.069 | 0.026 | 0.112 | 0.021 | 0.524* | 1.267 |
| | IMTP PF | | 0.002 | -0.004 | 0.008 | 0.003 | 0.136 | 1.581 |
| | RFD 0-200 | | 0.001 | -0.001 | 0.004 | 0.001 | 0.493 | 9.730 |
| | RFD 0-150 | | -0.002 | -0.004 | 0.000 | 0.001 | -0.684 | 7.990 |

Note: $R^2 = 0.379$ for step 1 ($p<0.001$), $\Delta R^2 = 0.013$ for step 2, $\Delta R^2 = 0.029$ for step 3, $\Delta R^2 = 0.059$ for step 4. *$p<0.01$, ** $p<0.001$



## Discussion

The aim of this investigation was to assess if CHV could be predicted by CMJ PI, IMTP PF and RFD in European Challenge Tour golfers. Table 2 shows that all four models significantly predicted the variance in CHV, however individual standardised beta coefficients revealed that CMJ PI was the only significant variable to predict changes in CHV in each model. Specifically, AIC revealed that model one produced the best fit to predict variance in CHV, with CMJ PI accounting for 37.9% of the variance in CHV. This supports recent research highlighting strong relationships between CMJ PI and CHV in highly skilled golfers (Wells et al., 2018). The findings from this investigation offer a great deal of practical significance, as golfers can be informed of the likely improvement in CHV through increasing CMJ PI. Specifically, multiplying the standardised beta coefficient for CMJ PI (0.616) by the standard deviation for CHV (2.75 m/s) results in a value of 1.69 m/s. As such, if a PGA Professional golf coach or S&C coach were able to increase a European Challenge Tour golfers' CMJ PI by one standard deviation (46.85 N·s), this would elicit an increase in CHV of 1.69 m/s. Consequently, this can be used as a benchmark for golfers who are looking to increase their CHV.

From Newton's Second Law of Motion, it can be stated that impulse (force x time) is directly proportional to the change in momentum (mass x velocity). Since a golfer's mass remains constant from shot to shot, it is the velocity that is affected through increasing the amount of force, or the time in which force acts during the downswing. Consequently, a golfer may increase impulse through pushing into the ground more (i.e. increasing vGRF) or by increasing the duration of their downswing, assuming no adverse reduction in mean force. This may be achieved by lengthening the backswing, or adopting a sequence that initiates the downswing from the ground-up. Along with these technical suggestions, golfers may also benefit from engaging in a resistance training and/or vertical jump interventions since previous research has indicated that these protocols have increased both impulse (Cormie, McGuigan, & Newton, 2010) and CHV (Fletcher & Hartwell, 2004, Doan et al, 2006). In addition, a recent investigation indicated that vertically oriented resistance training generated a statistically significant increase in vGRFs and ball velocity within highly skilled golfers (Driggers & Sato, 2017).

The CMJ is considered to be a slow stretch-shortening cycle (SSC), given that is takes longer than 250 ms to complete the movement (Schmidtbleicher 1992). This is of particular interest since the duration of the downswing has been suggested to last from 230-284 ms (Cochran & Stobbs, 1999; Tinmark et al., 2010). A major limitation with these studies however, is that the authors measured the duration of the downswing from the time the club was stationary at the top of the backswing to the moment of impact. As highly skilled golfers transition towards the top of the backswing, the force application to the ground initiates the start of the downswing, whilst the upper body continues to rotate away from the target (McTeigue et al., 1994), thus affording greater time to generate force. In addition, Nesbit and Serrano (2005) evidenced that highly skilled golfers initiate the downswing at a slower rate than lower skilled golfers. Given the force-velocity relationship, a golfer who initiates the downswing at a slower rate, will likely benefit from generating a greater amount of force. These forces, if transferred through the body's kinetic chain effectively, may transition into higher levels of velocity at the most distal segment in the swing (i.e. the clubhead).

Given the aforementioned suggestion that the downswing of highly skilled golfers is likely a longer duration than 230-284 ms, this could explain why both IMTP PF and RFD were unable to explain the variance in CHV. Since RFD was measured up to 200 ms, this window may not be long enough to assess the required force-time characteristics that relate to CHV. Further still, given that it can take up to 900 ms to achieve PF (Blazevich, 2011), there may not be the available time for golfers to achieve their maximum force generating capacity during the downswing. Considering the findings of this current investigation indicate that CMJ PI has a large significant relationship with CHV, PGA Professional golf coaches and S&C coaches should work together in order to design interventions aimed at increasing PI. The PGA Professional golf coach could support this, not only through technical refinements, but by advocating that golfers engage in S&C, due to the associated improvements in CMJ impulse (Cormie, McGuigan, & Newton, 2010). Specifically, it may be beneficial to perform CMJ's with an external load, since research has indicated that these jumps elicit significantly greater impulse than unloaded jumps (Mundy, Smith, Lauder & Lake, 2017). Further research however, should aim to establish the effects that different forms of training modalities (i.e. resistance training vs. loaded jumps) have on golfers' CHV.

## Conclusion

This is the first investigation that has sought to utilise a field-based design to examine the force generating capacity of European Challenge Tour golfers and the variance these measures have on CHV. The results of this investigation reveal that CMJ PI is a large significant predictor of the variance in European Challenge Tour golfers' CHV (37.9%). It is important to recognise, however, that there is a proportion of variance (62.1%) that remains unexplained. Despite this, the findings from this investigation suggest that if a European Challenge Tour golfer were to increase their CMJ PI by 46.85 N·s, this should result in an increase in CHV of 1.69 m/s. As such this procedure can be easily used to physically profile elite level golfers during a tournament season and facilitate the development of S&C interventions. Whilst the use of S&C programmes would be an appropriate avenue for increasing PI, PGA Professional golf coaches may also increase PI in their golfers through technical refinement. These technical changes should look to encourage golfers to utilise the ground more effectively, along with increasing the time in which force acts during the downswing. As such, an appropriate combination of both technical and physical training interventions aimed at enhancing impulse are likely to have a positive impact on CHV in elite golf populations and are therefore areas worthy of further investigation.

-Word count: 3756-

## Disclosure statement

The authors report no conflict of interest.

## References


Blazevich, A. (2011). The stretch-shortening cycle (SSC). In Cardinale, M., Newton, R., & Nosaka, K. ed., *Strength and Conditioning: Biological Principles and Practical Applications,* (pp. 209-221.). 1st ed, Oxford, John Wiley and Sons, Ltd.

Barretine, S., Fleisig, G. & Johnson, H. (1994). *Ground reaction forces and torques of professional and amateur golfers*, In: A. Cochran & M. Farraly (Eds.) Science and Golf II: Proceedings of the World Scientific Congress of Golf, London: E & FN Spon, pp 33-39.

Cheetham, P. & Broker, J. (2016). Kinematics sequence parameters expose technique differences between male and female professional golfers, *International Journal of Golf Science*, 5 (Suppl.), S19 – S20.

Cochran, A. & Stobbs, J. (1999). *Search for the Perfect Swing*, 6th ed, Chicago, IL, Triumph Books.

Cohen J.E. (1988). *Statistical Power Analysis for the Behavioral Sciences*. New Jersey, Lawrence Erlbaum Associates.

Cormie, P., McGuigan, M.R. & Newton, R.U. (2010). Adaptations in athletic performance after ballistic power versus strength training, *Medicine & Science in Sports & Exercise*, 42(8), 1582-1598.

De Witt, J.K., English, K.L., Crowell, J.B., Kalogera, K.L., Guilliams, M.E., Nieschwitz, B.E., Hanson, A.M. & Ploutz-Snyder, L.L. (2018). Isometric midthigh pull reliability and relationship to deadlift one repetition maximum. *The Journal of Strength & Conditioning Research*, 32(2), 528-533.

Doan, B.K., Newton, R.U., Kwon, Y-H. & Kraemer, W.J. (2006). Effects of physical conditioning on intercollegiate golfer performance. *Journal of Strength & Conditioning Research*, 20(1), 62-72.

Driggers, A.R. & Sato, K. (2017). The effects of vertically oriented resistance training on golf drive performance in collegiate golfers, *International Journal of Sports Science & Coaching*, 13(4), 598-606.

Field, A. (2014). *Discovering Statistics Using IMB SPSS Statistics*, London, Sage.

Fletcher, I.M., & Hartwell, M. (2004). Effect of an 8-week combined weights and plyometrics training program on golf drive performance. *Journal of Strength & Conditioning Research.* 18(1), 59-62.

Garhammer, J. (1993). A review of power output studies of Olympic and powerlifting: Methodology, performance prediction, and evaluation tests, *Journal of Strength & Conditioning Research*, 7(2), 76-89.

Haff, G.G., Ruben, R.P., Lider, J., Twine, C. & Cormie, P. (2015). A comparison of methods for determining the rate of force development during isometric midthigh clean pulls, *Journal of Strength & Conditioning Research*, 29(2), 386-395.

Hellström, J. (2008). The relation between physical tests, measures, and clubhead speed in elite golfers, *Annual Review of Golf Coaching,* 3(1), 85-92.

Hellström, J. (2009). Competitive elite golf: A review of the relationships between playing results, technique and physique, *Sports Medicine*, 39 (9), 723-741.

Hellström, J. (2017). Strength and conditioning for golf, In Toms, M. (ed.), *Routledge International Handbook of Golf Science*, (1st ed., pp. 326-335). Oxford, Routledge.

Hellström, J., Nilsson, J., & Isberg, L. (2014). Drive for dough. PGA Tour golfers' tee shot functional accuracy, distance and hole score. *Journal of Sports Sciences*, 32(5), 462-469.

Hume, P.A., Keogh, J. & Reid, D (2005). The role of biomechanics in maximising distance and accuracy of golf shots, *Sports Medicine,* 35(5), 429-449.

Leach, R.J., Forrester, S.E., Mears, A.C., & Roberts, J.R. (2017). How valid and accurate are measurements of golf impact parameters obtained using commercially available radar and stereoscopic optical launch monitors? *Measurement*, 112, 125-136.

Lewis, A.L., Ward, N., Bishop, C., Maloney, S. & Turner. A.N. (2016). Determinants of club head speed in PGA Professional golfers, *Journal of Strength & Conditioning research*, 30(8), 2266-2270.

Lynn, S., Noffal, G., Wu, W. & Vandervoort, A. (2012). Using principal component analysis to determine differences in 3D loading patters between beginner and collegiate level golfers, *International Journal of Golf Science*, 1(1), 25-41.

Lynn, S.K. & Wu, W. (2017). The use of ground reaction forces and pressures in golf swing instruction, In Toms, M. (ed.), *Routledge International Handbook of Golf Science*, (1st ed., pp. 15-25). Oxford, Routledge.

McTeigue, M., Lamb, S.R., Mottram, R. & Pirozzolo, F. (1994). Spine and hip motion analysis during the golf swing. In *Science and Golf II: Proceedings of the World Scientific Congress of Golf* (pp. 50-58). (edited by Cochran, A.J. and Farrally, M.R., London: E & FN Spon.

Mundy, P.D., Smith, N.A., Lauder, M.A. & Lake, J.P. (2017). The effects of barbell load on countermovement vertical jump power and net impulse, Journal of Sports Sciences, 35(18), 1781-1787.

Myers, J., Lephart, S., Tsai, Y-S., Sell, T., Smoliga, J. & Jolly, J. (2008). The role of upper torso and pelvis rotation in driving performance during the golf swing, *Journal of Sports Sciences*, 26(2), 181-188.

Nesbit, S.M., & Serrano, M. (2005). Work and power analysis of the golf swing, *Journal of Sports Science & Medicine,* 4, 520-533.

Oliver, M.H., Horan, S.A., Evans, K.A. & Keogh, J.W.L. (2016). The effect of a seven-week exercise program on golf swing performance and musculoskeletal measures, *International Journal of Sports Science & Coaching*, 11(4), 610-618.

Parchmann, C.J., & McBride, J.M. (2011). Relationship between functional movement screen and athletic performance, *Journal of Strength & Conditioning Research,* 25(12), 3378-3384.

Read, P.J. & Lloyd, R.S. (2014). Strength and conditioning considerations for golf, *Strength and Conditioning Journal*, 36(5), 24-33.

Read, P.J., Lloyd, R.S., De Ste Croix, M., & Oliver, J.L. (2013). Relationships between field-based measures of strength and power, and golf club head speed, *Journal of Strength & Conditioning Research,* 27(10), 2708-2713.

Schmidtbleicher, D. (1992). Training for power events. In *Strength and Power in Sports* (pp. 381-395). P.V. Komi, ed, London, United Kingdom, Blackwell scientific.

Tinmark, F., Hellström, J., Halvorsen, K. & Thorstensson, A. (2010). Elite golfers' kinematic sequence in full-swing and partial-swing shots, *Sports Biomechanics*, 9(4), 236-244.

Tirosh, O. & Sparrow, W.A. (2003). Identifying heel contact and toe-off using forceplate thresholds with a range of digital-filter cutoff frequencies, *Journal of Applied Biomechanics*, 19(2), 178-184.

TrackMan (2018). Available from: https://trackmangolf.com/what-we-track (Date Accessed $20^{th}$ March 2018).

Wells, J.E.T., Mitchell, A.C.S., Charalambous, L.H. & Fletcher, I.M. (2018). Relationships between highly skilled golfers' clubhead velocity and force producing capabilities during vertical jumps and an isometric mid-thigh pull, *Journal of Sports Sciences*, 36(16), 1847-1851.

Winter, D.A. (2009). *Biomechanics and motor control of human movement*, $4^{th}$ Ed, New Jersey, John Wiley and Sons Inc.