The effects of a six-week ballistic and plyometric training programme on female golfers' drive performance and neuromuscular characteristics

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Abstract

Golf-specific resistance training has become an additional method to increase drive distance and subsequent drive performance in recent years. However, the methods and subsequent benefits to such specific training modalities has thus far been isolated to male golfers. Female golfers may have differential outcomes from using identical golf-specific resistance training programmes to that of their male counterparts. To explore this unknown question in further detail, three separate investigations were undertaken within this thesis.

Firstly, a systematic review was undertaken of the current literature pertaining to the effects of resistance training on golf drive performance and neuromuscular characteristics. Various types of resistance training protocols are reported within the golf literature with the intention to increase club head speed (CHS) to further drive distance. Researchers in the majority of these studies have recruited male golfers and have shown clear improvements in CHS. However, to date, no researchers have examined the effects of ballistic and plyometric training for female golfers.

Secondly, ten skilled female golfers (HCP ≤ 10) were recruited to determine the reliability of an inertial measurement unit (IMU) to measure the rotational velocity of the lead wrist in the golf swing to use as an indicator for drive performance. Test-retest reliability was assessed over two separate occasions (separated by a minimum of six days). Based on the results, it was concluded that the use of an IMU on the lead wrist to assess rotational velocity during the golf swing is not a reliable measure (change in mean = -17.59%, coefficient of variation > 10%, intraclass correlation = 0.92). Therefore, this novel method of measuring rotational velocity of the golf drive motion was not included in further studies for measuring drive performance.

Lastly, two highly-skilled female golfers (HCP < 5) were recruited in a single-subject case design training intervention to assess the effectiveness of a six-week ballistic and plyometric training intervention on drive performance and neuromuscular characteristics. The drive performance and neuromuscular characteristics measures were taken on six occasions (*i.e.* weeks 0, 3, 6, 9,12 and 16) over a 16-week period (*i.e.* six-week pre-intervention [control], six-week intervention [experimental] and four-week post-intervention [non-training]). A six-week ballistic and plyometric training intervention elicited a substantial improvement in drive performance (*i.e.* CHS) in highly-skilled female golfers. The static side rotational throw reported the greatest improvement in all testing sessions compared to the dynamic side rotational throw. The countermovement jump showed the greatest improvement in peak power compared to the squat jump in all testing measures. Thus, the substantial improvements in upper- and lower-body power measures were transferred to golf performance as seen in the increase in CHS for both participants. Following a four-week post-intervention, there was a decrease in golf drive performance (*i.e.* CHS) and all upper-body power measures for both participants. However, there was also an increase in lower-body power (*i.e.* countermovement jump) following the four-week post-intervention for both participants. It is possible that the decrease in CHS may be due to the decrease in upper-body power measures.

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Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degrees or diploma of a university or other institution of higher learning.

Signature:

Date: 28.03.2018

Co-authored Works

The following three manuscripts are in preparation for submission for peer reviewed journal publication as a result of the work presented in this thesis.

Chau, A., Brown, S.R., Storey, A.G. (2018). The effects of resistance training on drive performance and neuromuscular characteristics for golfers: A systematic review. (Journal of Strength and Conditioning Research - Targeted Journal)

Authorship contribution: AC – 90%; SRB – 5%; AGS – 5%

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Authorship contribution: AC – 85%; SRB – 5%; JN – 5%; AGS – 5%

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Authorship contribution: AC – 90%; SRB – 5%; AGS – 5%

Author Contributions

The Master's candidate Anita Ya Ting Chau was the primary contributor to the research within this thesis and any analysis and interpretation from the associated results. All co-authors have approved the inclusion of the joint work in this thesis.

Masters candidate: Anita Ya Ting Chau

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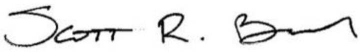

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List of Abbreviations

CHS	club head speed
cm	centimetre
CM	change in mean
CMJ	countermovement jump
CV	coefficient of variation
DCT	dynamic chest throw
deg	degree
deg/s	degrees per second
DSRT	dynamic side rotational throw
HCP	handicap
kg	kilogram
LPGA	ladies professional golf association
ICC	Intra class correlation coefficient
IMU	Inertial measurement unit
m	metre
Min	minute
m/s	metre per second
PGA	professional golf association
s	second
SCT	static chest throw
SJ	squat jump
SSRT	static side rotational throw
Yr	year

Ethics Approval

Ethical approval for this research was obtained from the Auckland University of Technology Ethics Committee (ethics number 17/41) on the 29th of March 2017 (see Appendix A).

Chapter One: Preface

1.1 Thesis Rationale

Golf is a popular sport throughout the world and has attracted players from all age, sex and skill ability for recreational purposes and/or as a competitive sport (Doan, Newton, Kwon, & Kraemer, 2006; Lephart, Smoliga, Myers, Sell, & Tsai, 2007). It is currently estimated that over 61 million people participate in the game of golf annually (Golftoday, 2018) and in 2016, golf reappeared at the Olympic Games after a 112-year hiatus. Ladies Professional Golfers Association (LPGA) tour statistics reported that the top five golfers with the longest drive distance have closer proximity to the hole and greater greens in regulation compare to those in the bottom five (LPGA, 2018). Thus, maximal golf drive distance and accuracy provides golfers with better opportunity to achieve an overall lower score.

To increase drive distance, golfers can explore equipment, technique, and/or neuromuscular performance related avenues. However, as the rules of golf impose design restrictions on golf clubs (R&A, 2018), golfers are left with two primary means to improve their drive performance; technical changes to improve swing mechanics and/or neuromuscular (*e.g.* upper- and lower-body power) improvements. However, once a player improves their technical ability, increasing a golfer's neuromuscular characteristics (*e.g.* strength and power producing ability) through golf resistance training programs should become a priority to help increase driving distance. Improvements in club head speed (CHS) have been observed following a period of strength (Alvarez, Sedano, Cuadrado, & Redondo, 2012; Doan et al., 2006; Fletcher & Hartwell, 2004), rehabilitation (Chen et al., 2010) and/or flexibility (Fradkin, Sherman, & Finch, 2004) training for male and female golfers. Furthermore, recent studies have reported improvements in CHS with ballistic and plyometric training for male golfers (Bliss, McCulloch, & Maxwell, 2015; Ghigiarelli, Gerland, & Cerra, 2015). However, the effects of ballistic and plyometric resistance training for female golfers remains unknown. Sex-related differences (*i.e.* neuromuscular characteristics, anatomical and physiological) may influence the ability to adapt to different types of golf resistance training protocols. As such, the results of golf resistance training interventions for male golfers cannot be necessarily generalised to female golfers. Therefore, the rationale behind this thesis was to fill this gap in the literature by investigating the effects of a six-week ballistic and plyometric training programme on female golfers' drive performance and neuromuscular characteristics.

Researchers of previous investigations have demonstrated the importance of rotational ability in golfers as golf swing rotational velocities influence CHS in male and female golfers (Chu, Sell, & Lephart, 2010; Okuda, Gribble, & Armstrong, 2010). Additionally, there are significant correlations between rotational speed ($r = 0.67$) (Read, Lloyd, Croix, & Oliver, 2013), power ($r = 0.54$) (Bradley, Moir, Davis, Witmer, & Cummings, 2009), and strength movements ($r = 0.71$) (Keogh et al., 2009), and CHS. Therefore, the ability for golfers to produce high levels of power, speed and rotational strength during the golf drive is required for high CHS and drive distance (Nesbit, 2005). Thus, to determine whether changes in neuromuscular characteristics (*i.e.* upper- and lower-body power) can positively effect drive performance, field-based testing measures are required to quantify changes in rotational velocity during the golf swing. Previous investigators have assessed swing mechanics using laboratory equipment such as the three-dimensional motion capture system to determine which parameters contributes to golf drive performance (*i.e.* angular velocity and displacement) (Beak et al., 2013; S. J. Brown et al., 2011; Horan, Evans, & Kavanagh, 2011; Horan, Evans, Morris, & Kavanagh, 2010; Horan & Kavanagh, 2012; Kadowaki, Kobayashi, & Watanabe, 2006; Myers et al., 2008). However, it is not practical to use three-dimensional motion capture system in a field-based setting to measure rotational velocity of the golf swing. Therefore, other more practical-based measures must be explored, and the reliability of such measures must be assessed. Thus, the rationale behind Chapter Three was to determine the reliability of an inertial measurement unit (IMU) placed on the lead wrist to measure changes in rotational velocity of the golf swing. Following the establishment of the testing methodology, the purpose of Chapter Four was to investigate the overarching question of; 'what are the effects of a six-week ballistic and plyometric training programme on female golfers' drive performance and neuromuscular characteristics'.

1.2 Research Aims and Hypothesis

The aims of this thesis were to:

1) Examine and compare the current literature on resistance training for golfers with emphasis on the (a) muscular activation patterns during the golf swing; (b) sex-related difference in golf swing mechanics; and (c) effects of strength and power training protocols on golf drive performance and neuromuscular characteristics.
2) Establish the reliability of IMU to measure rotational velocity of the golf drive when placed on the lead wrist.
3) Determine the effects of a six-week ballistic and plyometric training programme on female golfers' drive performance and neuromuscular characteristics.

The following hypotheses were generated for the studies undertaken within this thesis:

1) The IMU (when placed on the lead wrist) will produce reliable (intraclass correlation ≥ 0.70, coefficient of variation ≤ 10%) measures of rotational velocity of the golf drive.
2) The ballistic and plyometric training programme will improve the golf drive performance (*i.e.* CHS) and neuromuscular (*i.e.* upper- and/or lower-body power measures) characteristics in highly-skilled female golfers (HCP < 5).

1.3 Research design

Three studies were undertaken to achieve the above hypothesis within this thesis.

1) A systematic review to determine the effects of resistance training on the muscle activation patterns during the golf swing, influence of sex-related differences on the biomechanics of the downswing and adaptation responses to golf resistance training programmes.

2) A repeated measures analysis was used to establish the test-retest reliability of the IMU device to assess rotational velocity of the golf swing when placed on the lead wrist.
3) A single-subject research design involving a training intervention with two highly-skilled female golfers to investigate the effects of a six-week ballistic and plyometric training programme on drive performance and neuromuscular characteristics.

1.4 Thesis originality

The thesis can be observed as original and compliments the current literature knowledgebase in the following areas:

- There are no systematic literature reviews investigating the muscle activation patterns during the golf swing, influence of sex-related differences on the biomechanics of the downswing and adaptation responses to golf resistance training programmes.

- There are no studies investigating the reliability of the IMU to assess changes in golf drive performance when the IMU is placed on the lead wrist. Additionally, there are no studies using IMU devices to assess changes in drive performance following golf training programmes.

- There is no research assessing the effectiveness of ballistic and plyometric training on female golfers' drive performance and neuromuscular characteristics.

1.5 Thesis organisation

The following thesis consists of five chapters. Chapter One introduces the thesis topic and outlines the rationale and organisation. Chapter Two is a systematic review of the current golf literature that primarily focuses on the muscle activation patterns during the golf swing, sex-related differences of the downswing and effects of resistance training on drive performance and neuromuscular characteristics. Chapter Three is an investigation of the reliability of an IMU when placed on the lead wrist to measure the rotational velocity of the golf swing. Novel findings and practical applications of the testing protocols are detailed in the discussion of Chapter Three. Chapter Four is a single-subject research design investigating the effects of six-week ballistic and plyometric training on female golfers' drive performance and neuromuscular characteristics. Interpretation of the effects of the ballistic and plyometric training on female golfers' drive performance and neuromuscular characteristics is given in the discussion along with practical applications and a direction for future research. Chapter Five is a summary of the complete thesis which provides synthesised conclusions from the thesis and identifies areas of further research based on the limitations and areas that are deemed to be beyond the scope of the current thesis.

Chapter Two:

The effects of resistance training on drive performance and neuromuscular characteristics for golfers: A systematic review

2.1 Preface

The purpose of this chapter is to review the current literature pertaining to the effects of resistance training on drive performance and neuromuscular characteristics for golfers. In addition, emphasis is placed on literature that provides an understanding of the application of golf-specific resistance training interventions. Furthermore, the role that sex-related differences may have on drive performance and the associated adaptations arising from resistance training interventions are also investigated for golfers.

2.2 Introduction

Golf has previously been viewed as a skill-based sport wherein golfers primarily focus on developing optimal swing mechanics and low movement variability in comparison to developing neuromuscular characteristics to improve drive performance (Horan & Kavanagh, 2012; Hume, Keogh, & Reid, 2005). Maximal distance and accuracy are the main outcomes of an optimal golf drive. Club selection and shot strategy remain key components throughout a round of golf. However, golf drive distance has the highest correlation with handicap (HCP) (r = 0.95), viewed as a measure of golfing ability, where the lower the HCP the more skilled the player is (Fradkin et al., 2004). According to Fletcher and Hartwell (2004), CHS during the full golf swing is significantly correlated (r = 0.86) with drive distance; therefore the greater the CHS the further the drive distance. To increase CHS, golfers require enhanced rotational power, strength and flexibility (Keogh et al., 2009; Sell, Tsai, Smoliga, Myers, & Lephart, 2007). Previous investigators have reported sex-related differences in swing mechanics, endpoint movement variability, neuromuscular and physiological characteristics which subsequently result in lower CHS and drive distances for female golfers compared to male golfers (Horan et al., 2011; Horan & Kavanagh, 2012; Myers et al., 2008). An understanding of the muscle activities within the different phases of the golf swing (*i.e.* backswing, downswing and follow-through) may assist with the prescription of exercises that are targeted at improving CHS (Aggarwal, Shenoy, & Sandhu, 2008; Farber, Smith, Kvitne, Mohr, & Shin, 2009; Horton, Lindsay, & Macintosh, 2001).

At present, golf tracking field-based systems such as Flightscope launch monitor are able to measure CHS and golf club angle of attack (among other performance metrics) (Read, Lloyd, et al., 2013). The metrics derived from Flightscope launch monitor are specific to what is happening at the level of the clubhead at ball impact. However, further investigation is required to assess the effectiveness of field-based technologies that can assess rotational velocity of the upper-extremities (*e.g.* wrist) during the golf swing. The IMU is such a device that can measure rotational velocity, however, at present, a paucity of literature exists on the reliability regarding the application of IMU to on upper-extremities to assess rotational velocity of the golf swing. To improve CHS golfers can either: 1) improve swing mechanics; 2) decrease endpoint movement variability in swing technique; and/or 3) utilise golf-specific resistance training. Improvements in CHS are limited for skilled golfers (HCP ≤ 10) due to their well-established swing mechanics (*i.e.* refined and repeatable swing technique) and low endpoint movement variability (*i.e.* the ability to hit the ball consistently to achieve maximal drive distance and accuracy) compared to less skilled golfers (HCP ≥ 11) (Chu et al., 2010; Sell et al., 2007; Zheng, Barrentine, Fleisig, & Andrews, 2008). However, previous researchers has indicated that golfers may experience improvements in CHS and overall golf performance following golf-specific resistance training programmes which positively influence kinetic and kinematic variables (*e.g.* impulse, peak force, peak velocity, and rate of force production) (Ghigiarelli et al., 2015; Lamberth, Hale, Knight, Boyd, & Luczak, 2013; Lephart et al., 2007). Therefore, this systematic review of the literature will firstly determine the electromyography (EMG) muscle activity that underpin the biomechanics of the golf swing when using the golf driver. Secondly, the biomechanics in relation to sex-related difference of the golf swing when using the golf driver will be examined. Thereafter, data on golf resistance training will be reviewed to determine the effects on the drive performance. Finally, golf-specific recommendations will be provided for potential future research to improve drive performance.

2.3 Systematic Review Search Methods

2.3.1 Search parameters and criteria. A systematic search of the literature was undertaken using the following databases: Scopus, SPORTDiscus, Google Scholar, Web of Science, PubMed and Medline. The databases were searched online up to May 2017. The following Boolean keyword phases were used: (Golf) AND (biomechanic* OR swing) AND (male OR female) AND (training OR program* OR intervention*) AND (drive*) AND (EMG OR electromyography AND muscle*). A manual screen of the reference list of relevant literature was used to find further articles. Articles were deemed appropriate for use through the following inclusion criteria: 1) the literature was published in English; 2) the articles were from peer-reviewed journals from 1980 to May 2017; 3) muscle activation was in relation to the generation of CHS during the golf drive; 4) sex-related differences were in relation to the biomechanics of the golf drive and subsequent generation of CHS; 5) changes in CHS were a determining factor of golf drive performance and/or neuromuscular characteristics following golf resistance training interventions.

The exclusion criteria were: 1) the literature was not published in English language and was not from peer-reviewed journals; 2) biomechanical and/or EMG related studies performed in injured golfers; 3) biomechanical analysis on the foot and grip pressure and/or foot pressure in relation to CHS which did not measure thorax and pelvis segments; 4) biomechanical investigations of the golf swing that did not report and/or measure thorax and pelvis segments for male and/or female golfers; 5) golf resistance training and/or biomechanical investigations that did not report separate results for male and female; 6) acute golf resistance training interventions of <1 week and/or golf warm up protocols; 7) investigations that measured changes in HCP following golf resistance training interventions but did not measure golf drive performance (*i.e.* CHS, drive distance, rotational velocity); 8) biomechanical investigations of the golf swing using irons and/or wedge irons and/or putter; 9) qualitative based investigations into the golf swing of male and/or female players; 10) investigations that assessed the influence of golf shaft properties (*i.e.* equipment related variables) on swing mechanics and/or CHS.

2.3.2 Search results. The initial search procedure yielded 1,557 total records. After removing duplicates, 420 publications were retained for the article selection process. Title section excluded 316 records, and abstract selection excluded 30 records. The remaining 74 records were further examined using the specified inclusion/exclusion criterion, leaving a total of 29 studies (see Figure 1).

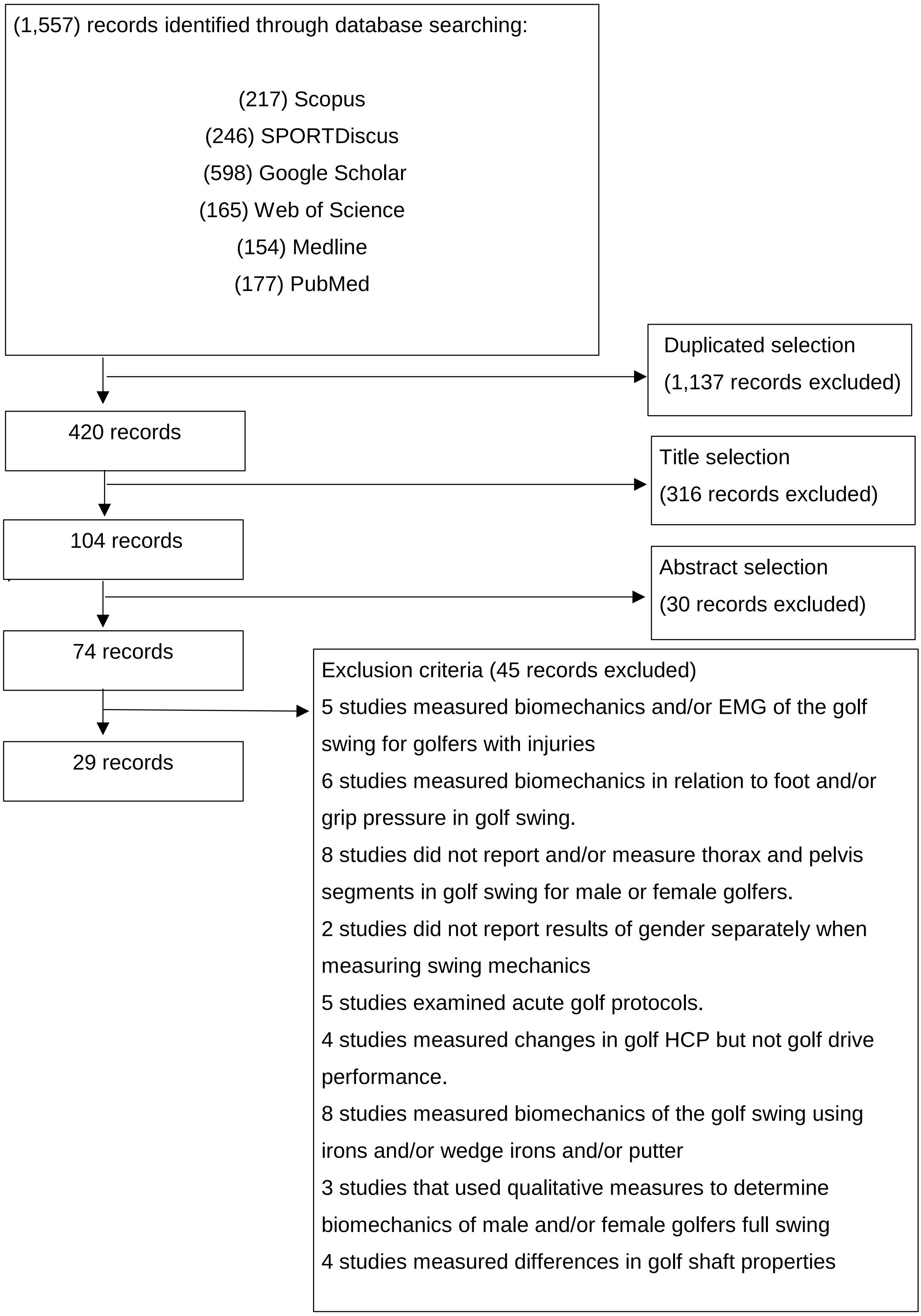


Figure 1. Search results flow-chart.

2.3.3 Methodological quality assessment. A quality assessment rating was included due to the differences in methodologies within the identified golf studies. The methodological quality assessment (Table 1) used in this review was adopted from similar quality assessments

(S. R. Brown, 2016) and was further developed for golf studies in relation to drive performance. Thus, the quality assessment rating allows for the comparison between golf studies in relation to the drive performance and the results. Due to the methodological differences in studies, the mean and standard deviation may not reflect a true assessment of the total included studies therefore the range of mean score was included. Of the 29 studies assessed, there was a mean score of 12.8 / 20 (range: 9 to 18). All studies reported participants' characteristics, demographics, and inclusion/exclusion criterion. All studies clearly or partially reported repeatable description of methods and clearly defined outcome variables and appropriate statistical analyses. The studies with the highest quality assessment rating also reported proper training and practice trials, power analysis and/or test-retest reliability of measurement devices and assessment protocols. Golf studies which have lower quality rating scores may require greater consideration and caution when analysing and interpreting the results.

Table 1 *Methodological Quality Assessment*

Questions	Criteria	Hegedus et al. (2016)	Alvarez et al. (2012)	Doan et al. (2006)	Bliss et al. (2015)	Lephart et al. (2007)	Fletcher & Hartwell, (2004)
1	Power analysis was performed and justification of study sample size.	2	0	2	0	0	0
2	Athlete demographics were clearly defined: Gender, age, body-height, body mass and HCP.	2	2	2	2	2	2
3	Athlete characteristics were clearly defined: Sport, experience or golf skill level and level of play at the time of test.	2	2	2	2	2	2
4	Inclusion and exclusion criteria were clearly stated for athletes.	2	2	2	2	1	1
5	Athletes or groups of athletes were similar at baseline or differences were accounted for and explained.	2	2	2	2	1	2
6	Proper training and practice trials of the test were given to the athletes allowing for adequate familiarization.	1	2	2	1	1	2
7	Details of the test was given to allow replication of the test (testing devices, type of testing, number of trials, duration of rest and intensity).	2	2	1	2	2	1
8	Test-retest reliability of measurement device reported.	1	2	0	1	2	0
9	Outcome variables were clearly defined.	2	2	2	2	2	2
10	Statistical analyses were appropriate.	2	2	2	2	2	2
	Total score (maximum 20 points)	18	18	17	16	15	14

Key: 0, clearly no; 1, maybe or inadequate information; 2, clearly yes

Table 1

Continued

Questions	Criteria	Kim, (2010)	Lamberth et al. (2013)	Ghigiarelli et al. (2015)	Weston et al. (2013)	Brown et al. (2011)	Horan & Kavanagh, (2012)
1	Power analysis was performed and justification of study sample size.	0	0	0	0	0	0
2	Athlete demographics were clearly defined: Gender, age, body-height, body mass and HCP.	2	1	2	2	2	2
3	Athlete characteristics were clearly defined: Sport, experience or golf skill level and level of play at the time of test.	2	2	2	2	2	2
4	Inclusion and exclusion criteria were clearly stated for athletes.	2	2	1	1	1	1
5	Athletes or groups of athletes were similar at baseline or differences were accounted for and explained.	2	2	1	1	2	2
6	Proper training and practice trials of the test were given to the athletes allowing for adequate familiarization.	0	2	1	1	2	2
7	Details of the test was given to allow replication of the test. (testing devices, type of testing, number of trials, duration of rest and intensity).	2	1	1	1	1	1
8	Test-retest reliability of measurement device reported.	0	0	2	2	0	0
9	Outcome variables were clearly defined.	2	2	2	2	2	2
10	Statistical analyses were appropriate.	2	2	2	2	2	2
	Total score (maximum 20 points)	14	14	14	14	14	14

Key: 0, clearly no; 1, maybe or inadequate information; 2, clearly yes

Table 1

Continued

Questions	Criteria	Horan et al. (2011)	Horan et al. (2010)	Farber et al. (2009)	Thompson & Osness, (2004)	Jobe et al. (1989)	Fradkin et al. (2004)
1	Power analysis was performed and justification of study sample size.	0	0	0	0	0	0
2	Athlete demographics were clearly defined: Gender, age, body-height, body mass and HCP.	2	2	1	1	1	1
3	Athlete characteristics were clearly defined: Sport, experience or golf skill level and level of play at the time of test (HCP).	2	2	2	1	2	2
4	Inclusion and exclusion criteria were clearly stated for athletes.	1	1	1	2	1	1
5	Athletes or groups of athletes were similar at baseline or differences were accounted for and explained.	2	2	2	2	2	2
6	Proper training and practice trials of the test were given to the athletes allowing for adequate familiarization.	1	1	1	0	0	1
7	Details of the test was given to allow replication of the test (testing devices, type of testing, number of trials, duration of rest and intensity).	1	1	2	1	2	1
8	Test-retest reliability of measurement device reported.	0	0	0	1	0	0
9	Outcome variables were clearly defined.	2	2	2	2	2	2
10	Statistical analyses were appropriate.	2	2	2	2	2	2
	Total score (maximum 20 points)	13	13	13	12	12	12

Key: 0, clearly no; 1, maybe or inadequate information; 2, clearly yes

Table 1

Continued

Questions	Criteria	Beak et al. (2013)	Aggarwal et al. (2008)	Kao et al. (1995)	Watkins et al. (1996)	Myers et al. (2008)	Thompson et al. (2007)
1	Power analysis was performed and justification of study sample size.	0	0	0	0	0	0
2	Athlete demographics were clearly defined: Gender, age, body-height, body mass and HCP.	2	1	1	1	1	2
3	Athlete characteristics were clearly defined: Sport, experience or golf skill level and level of play at the time of test (HCP).	2	2	2	2	2	0
4	Inclusion and exclusion criteria were clearly stated for athletes.	1	1	1	1	1	1
5	Athletes or groups of athletes were similar at baseline or differences were accounted for and explained.	2	2	2	1	1	1
6	Proper training and practice trials of the test were given to the athletes allowing for adequate familiarization.	0	1	1	1	0	1
7	Details of the test was given to allow replication of the test (testing devices, type of testing, number of trials, duration of rest and intensity).	1	1	1	1	2	2
8	Test-retest reliability of measurement device reported.	0	0	0	0	0	0
9	Outcome variables were clearly defined.	2	2	2	2	2	2
10	Statistical analyses were appropriate.	2	2	2	2	2	2
	Total score (maximum 20 points)	12	12	12	11	11	11

Key: 0, clearly no; 1, maybe or inadequate information; 2, clearly yes

Table 1

Continued

Questions	Criteria	Bechler et al. (2008)	Pink et al. (1990)	Chen et al. (2010)	Loock et al. (2012)	Hetu et al. (1998)
1	Power analysis was performed and justification of study sample size.	0	0	0	0	0
2	Athlete demographics were clearly defined: Gender, age, body-height, body mass and HCP.	1	1	1	1	1
3	Athlete characteristics were clearly defined: Sport, experience or golf skill level and level of play at the time of test (HCP).	2	2	2	2	1
4	Inclusion and exclusion criteria were clearly stated for athletes.	1	1	1	1	1
5	Athletes or groups of athletes were similar at baseline or differences were accounted for and explained.	1	0	2	2	0
6	Proper training and practice trials of the test were given to the athletes allowing for adequate familiarization.	0	0	0	0	1
7	Details of the test was given to allow replication of the test (testing devices, type of testing, number of trials, duration of rest and intensity).	1	2	1	1	1
8	Test-retest reliability of measurement device reported.	0	0	0	0	0
9	Outcome variables were clearly defined.	2	2	1	2	2
10	Statistical analyses were appropriate.	2	2	1	2	2
	Total score (maximum 20 points)	10	10	9	9	9

Key: 0, clearly no; 1, maybe or inadequate information; 2, clearly yes

2.4 Muscle Activation in Relation to the Biomechanics of the Golf Drive

The golf swing is a sequential movement pattern and therefore requires coordination of various muscle groups. The golf swing comprises of four primary phases: 1) backswing, 2) downswing, 3) acceleration and, 4) follow-through (McHardy & Pollard, 2005). The backswing starts with the rotation of the body away from the ball. The downswing (also known as forward swing) begins from the end of the backswing until the club is horizontal to the ground and is followed by the acceleration of the club to ball impact. Finally, the follow-through occurs after ball impact when the body segments rotate to the end of motion. The following descriptions of the muscle activation patterns during the golf swing will be in relation to a right-handed golfer whereby the right side of their body is known as the trail side and the left side is known as the lead side (Aggarwal et al., 2008; Bechler, Jobe, Pink, Perry, & Ruwe, 1995; Farber et al., 2009; Jobe et al., 1989; Kao et al., 1995; Pink et al., 1990; Pink, Perry, & Jobe, 1993; Watkins et al., 1996).

The backswing phase is initiated by the external and internal oblique muscles of the lead and trail side of the trunk, respectively, helping to facilitate the rotation of the trunk away from the ball (Pink et al., 1993; Watkins et al., 1996). The muscles most highly activated during the backswing are the right erector spinae, left and right abdominal oblique, right latissimus dorsi, left and right pronator teres and the right gluteus maximus (Table 2) (Farber et al., 2009; Kao et al., 1995; Watkins et al., 1996). During the backswing, skilled male golfers (HCP ≤ 10) typically demonstrate higher muscle activity of the lead external oblique and trail internal oblique compared with their less skilled counterparts (HCP ≥ 11) (Aggarwal et al., 2008). So while the oblique muscles generally aid in trunk rotation for all golfers, the higher activation found in skilled golfers also contributes to higher CHS (Aggarwal et al., 2008). During the backswing, the erector spinae of the trail side acts as a stabiliser during the rotation of the trunk (Pink et al., 1993; Watkins et al., 1996). As the trunk rotates away from the ball in the backswing, the trapezius, levator scapulae and rhomboid muscles on the trail side are activated to help facilitate the retraction and elevation of the scapula (Kao et al., 1995). The lead pectoralis major and anterior deltoids assist protraction and internal rotation of the scapula, helping to position the hands and club at the top of the backswing in preparation for the downswing (Pink et al., 1990). The subscapularis, infraspinatus and supraspinatus work together as external rotators, abductors and glenohumeral stabilisers due to large range of motion in the backswing (Kao et al., 1995). Meanwhile, the semimebranous and biceps femoris work together to resist knee extension, which is suggested to facilitate in greater trunk rotation (Bechler et al., 1995). The rotation of the thorax against the pelvic muscles in the backswing encourages a stretch-reflex in the core musculature (*i.e.* internal and external oblique muscle activation) enhancing the subsequent concentric action and helping to generate greater rotational velocity and force for CHS (Aggarwal et al., 2008). It is widely accepted in the golfing community that a greater emphasis is placed on the downswing to generate CHS compared to the backswing (Aggarwal et al., 2008; Pink et al., 1990; Watkins et al., 1996).

The downswing is initiated by the gluteus maximus, gluteus medius, biceps femoris and semimembranosus of the trail leg. These muscle groups promote extension of the hip, while transferring the weight from the trail leg to the lead leg resulting in a rotation of the pelvis towards the target line (Bechler et al., 1995; McHardy & Pollard, 2005; Watkins et al., 1996). The muscles most highly activated in the downswing are the right abdominal oblique, upper serratus, rhomboids, middle trapezius, right latissimus dorsi, right and left pectoralis major, right and left gluteus maximus and right gluteus medius (Table 2) (Bechler et al., 1995; Jobe et al., 1989; Kao et al., 1995; Pink et al., 1990; Watkins et al., 1996). It is thought that the hip joint provides a pathway for transmission of forces from lower- to upper-extremities (Pink et al., 1990). The high level of muscle activity in the gluteus maximus is due to its role as a hip stabiliser and it is utilised as a base-of-support for the rapid rotation of the trunk musculature (Bechler et al., 1995; Watkins et al., 1996). Interestingly, the right erector spinae muscle activity was found to be greater in skilled male golfers (HCP ≤ 10) compared to lesser skilled male golfers (HCP ≥ 11); suggesting high erector spinae muscle activity may contribute to greater CHS (Aggarwal et al., 2008). Although the forces are produced from the ground up (*i.e.* lower extremities to upper extremities), the rapid hip rotation initiates a stretch reflex through the core musculature and leads to increases in internal and external oblique activation for high CHS (Pink et al., 1990; Watkins et al., 1996). The muscle activity of the levator scapulae, rhomboids and trapezius in the lead arm act to retract and elevate the lead scapular to accelerate the golf club in the downswing for CHS and to re-orientate the club to ball impact and follow-through (Kao et al., 1995). The latissimus doris is used to stabilise the glenohumeral joint, while the pectoralis major adducts and internally rotates the shoulder to generate rotational power throughout the downswing (Jobe et al., 1989; Pink et al., 1990). Farber et al. (2009) found significantly greater muscle activation in the lead pronator teres in professional male golfers compared to less skilled/amateur golfers in the downswing. This finding was possibly due to the differences in swing technique in which professional golfers rotate the golf club through the arc of the swing using the lead arm rather than using the trail arm to push the club through the swing. Collectively, the downswing to ball impact phase has higher muscle activation compared to all phases of the golf swing (Aggarwal et al., 2008; Jobe et al., 1989; Kao et al., 1995; Pink et al., 1990; Watkins et al., 1996). During the follow-through, high muscle activity predominately occurs in the upper serratus, left infraspinatus, pectoralis major and right gluteus medius (Table 2) (Bechler et al., 1995; Jobe et al., 1989; Kao et al., 1995; Pink et al., 1990). The oblique muscles are activated to gradually decelerate the trunk rotation after ball impact until the end of the movement (Aggarwal et al., 2008; Watkins et al., 1996). The gluteus medius continue to adduct and extend the trail hip to promote the pelvic rotation, while the lead biceps femoris and vastus medialis provide a stable base-of-support to the end of the follow-through (Bechler et al., 1995).

There are some inherent limitations when comparing studies of muscular factors in relation to the golf drive. These limitations, in part, are due to; 1) differences in the placement of the surface electrodes, 2) absence of specific information on the methodology used to determine signals and, 3) no defined criteria for timing parameters (*i.e.* onset and offset time for EMG) (Aggarwal et al., 2008; Jobe et al., 1989; Kao et al., 1995; Pink et al., 1990). Previous investigators examining the role of the trunk musculature have used surface EMG (Pink et al., 1993; Watkins et al., 1996) while others examining the shoulder (Jobe et al., 1989; Kao et al., 1995; Pink et al., 1990), lower-limb (Bechler et al., 1995) and forearm muscles (Farber et al., 2009) have used fine wire electrodes. Additionally, no study included a description of the participants' golf swing (*i.e.* modern golf swing, classic golf swing or hybrid golf swing – refer to section 2.5 for a description of golf swings) which is of great practice importance as different types of swing mechanics may produce different muscle activation patterns. Therefore, further research is required to determine the effects of different swing mechanics (*i.e.* modern compared to classic golf swing) on the subsequent EMG outputs.

At present, the sequencing of muscle patterns during a golf swing may only be generalised for skilled (HCP ≤ 10) and/or professional male golfers as lesser skilled male golfers (HCP ≥ 11) may have greater variation of muscle firing patterns (Aggarwal et al., 2008; Jobe et al., 1989; Kao et al., 1995; Pink et al., 1990). Furthermore, due to the aforementioned sex-related difference in swing mechanics, such findings cannot yet be generalised to female players. Therefore, future studies are required to determine the sex-related differences in muscle activation of thorax and pelvis regions during the golf swing for both skilled and unskilled golfers.

Table 2
Summary of Electromyography Studies on Muscles Activated in the Different Phases of the Full Golf Swing using a Driver (*n* = 7)

Study	Sample	Programme protocol	Muscles outcome measure	Muscle activation		
	Right handed golfers			Backswing	Downswing	Follow-through
Jobe et al. (1989)	n = 6M age = 30 to 42 n = 7F age = 24 to 44 HCP = Pro	Compares the EMG firing patterns of normal shoulder musculature in male and female pro golfers.	MMT (%): PM, LD, AD, IS, SS	SS (R): M = 21 ± 10 F = 29 ± 26 IS (R): M = 24 ± 12 F = 29 ± 30	LD (R): M = 43 ± 35 F = 58 ± 41 LD (L): M = 48 ± 18 F = 43 ± 35 PM (R): M = 112 ± 87 F = 78 ± 43 PM (L): M = 122 ± 100 F = 64 ± 26	SS (L): M = 31 ± 29 F = 26 ± 3 IS (L): M = 61 ± 37 F = 60 ± 30 AD (R): M = 13 ± 13 F = 45 ± 38
Pink et al. (1990)	n = 6M age = 30 to 42 n = 7F age = 24 to 44 HCP = Pro	Analyse the EMG activity in eight shoulder muscles of both the right and left arms during the golf swing for shoulder function.	MMT (%): PM, LD, SB, IS, SS, AD	IS (R): backswing (27*) compared to acceleration (7) or late follow-through (9) SS (R): backswing (25*) compared to follow-through (7)	PM (R): downswing (64) and acceleration (93) compared to backswing (12) LD (R): downswing (50) compared to backswing (9) LD (L): downswing (46) compared to takeaway (17) and follow-through (32)	PM (right): follow-through (74) compared to backswing (12) IS (left): follow-through (61) compared to backswing (14) downswing (16) and acceleration (27)

Table 2
Continued

Bechler et al. (1995)	n = 13M and 3F age = 27 to 59 HCP < 3	EMG analysis of hip in the golf swing for pro golfers.	MMT (%): UGM, LGM, GMD	Trail leg: GMD (21) UGM (20) LGM (16) Lead leg: GMD (7) UGM (9) LGM (7)	Trail leg: GMD (74) UGM (100) LGM (98) Lead leg: GMD (36) UGM (50) LGM (50)	Trail leg: GMD (59) UGM (13) LGM (12) Lead leg: GMD (20) UGM (47) LGM (39)
Kao et al. (1995)	n = 15M age = 25 to 55 HCP < 5	To describe the role of the scapular muscles in the golf swing.	MMT (%): LS, RB, UT, MT, LT, US, LSS	Trail arm: LS = 29 ± 19 RB = 30 ± 18 UT = 24 ± 14 MT = 37 ± 12 LT = 52 ± 28 US 6 ± 4 LSS = 9 ± 5 Lead arm: LS = 5 ± 3 RB = 7 ± 13 UT = 5 ± 4 MT = 3 ± 3 LT = 7 ± 10 US = 30 ± 15 LSS = 27 ± 11	Trial arm: LS = 38 ± 39 RB = 46 ± 27 UT = 4 ± 4 MT = 18 ± 24 LT = 17 ± 12 US = 58 ± 39 LSS = 29 ± 17 Lead arm: LS = 42 ± 20 RB = 68 ± 27 UT = 29 ± 26 MT = 51 ± 26 LT = 49 ± 27 US = 20 ± 29 LSS = 20 ± 21	Trial arm: LS = 12 ± 12 RB = 21 ± 12 UT = 23 ± 19 MT = 26 ± 21 LT = 22 ± 22 US = 52 ± 18 LSS = 47 ± 25 Lead arm: LS= 39 ± 26 RB = 26 ± 26 UT = 34 ± 29 MT = 21 ± 18 LT = 20 ± 16 US = 31 ± 18 LSS = 29 ± 20

Table 2
Continued

Watkins et al. (1996)	n = 13M age = N/A HCP = Pro	Dynamic EMG analysis of trunk musculature in pro golfers.	MMT (%): AO, GM, ES, URA, LRA	AO (R and L) = 52 and 63 respectively GM (R and L) = 84 and 35 respectively ES (R and L) = 55 and 35 respectively RA (R and L) = 30 and 31 respectively.	AO (R and L) = 59 and 38 respectively GM (R and L) = 21 and 53 respectively ES (R and L) = 38 and 44 URA = 35 LRA = 34	AO (R and L) = 34 and 39 respectively GM (R and L) = 8 and 14 respectively ES (R and L) = 15 and 19 respectively URA = 9 LRA = 16
Aggarwal et al. (2008)	n = 22M age = 21.5 ± 3.4 HCP = 0-8 BM = N/A height = N/A HCP = 10-18	Compared muscle activation amplitudes in the trunk region of two different skill level golfers during golf swing.	MVIC (%): ES, EO, IO	ES (L): LS = 29.6, HS = 28.21 ES (R): LS = 35.15, HS = 29.79 EO (L): HS = 22.36, LS =16.58 EO (R): LS = 13.14, HS = 21.33 IO (L): HS = 21.53, LS = 18.92 IO (R): HS = 23.05, LS = 19.7	ES (L): HS = 30.78, LS = 33.78 ES (R): HS = 36.37, LS = 31.89 EO (R): LS = 24.83, HS = 33.37 EO (L): HS = 24.27, LS = 23.8 IO (R): HS = 25.76, LS = 25.16 IO (L): HS = 33.32, LS = 30.6	E.S (L): HS = 30.75, LS = 35.52 ES (R): HS = 34, LS = 32.74 EO (R): HS = 31.39, LS = 31.6 EO (L): HS = 29.17, LS = 26.16 IO (R): HS = 30.43, LS = 26.7 I.O (L): HS = 35.05, LS = LS 31.23

Table 2
Continued

Farber et al. (2009)	n = 10M Pro golfers and 10M Am golfers age = N/A	Compare the activity of forearm muscles in pro golfers versus amateur golfers.	MMT (%): PT	Trial arm = Pro vs Am (120.9 vs 57.4*).	Trial arm = Pro vs Am (104.8 vs 53.1*; P = .08). Lead arm = Pro vs Am (104.8 MMT vs 53.1*, P = .08).	N/A

Key: * statistically significant p < 0.05. AO = abdominal oblique; Age = years old; AD = anterior deltoids; Am = amateur; AC = asymptomatic control; CLBP = chronic lower back pain; ES = erector spinae; EO = external oblique; F = female; GM = gluteus maximus; GMD = gluteus medius; HCP = handicap; HS = high skilled; IS = infraspinatus; IO = internal oblique; LD = latissimus dorsi; lead = the left side; LS = levator scapulae; L = left; LSS = lower serratus; LS = low skilled; LT = lower trapezius; LGM = lower gluteus maximus; LRA = lower rectus abdominis; M = male; MMMT = maximum manual muscle test; MMT = manual muscle strength test; MVC = maximal voluntary contraction; MVIC = maximum voluntary isometric contractions; MT = middle trapezius; PM = pectoralis major; Pro = professional; PT = Pronator teres; RA = rectus abdominis; RB = rhomboid muscles; R = right, SB = subscapularis; Trail = the right side; UGM = upper gluteus maximus; URA = upper rectus abdominis; US = upper serratus; UT = upper trapezius.

2.5 Biomechanics in Relation to Sex-Related Differences of the Golf Drive

Male golfers' anthropometry and neuromuscular characteristics substantially differ from female golfers. Male golfers are generally taller and have a greater body-mass and arm span when compared to female golfers (S. J. Brown et al., 2011; Horan et al., 2011; Horan et al., 2010). The longer arm span of males helps to generate greater torque which contributes to the greater CHS and drive distances (S. J. Brown et al., 2011; Horan et al., 2011; Horan et al., 2010). Furthermore, from a physiological standpoint, several authors have reported sex-related differences for muscle thickness, fiber length and pennation angle in both upper (Abe, Brechue, Fujita, & Brown, 1998; Ichinose, Kanehisa, Ito, Kawakami, & Fukunaga, 1998) and lower-extremities (Abe et al., 1998; Chow et al., 2000; Kubo, Kanehisa, & Fukunaga, 2003). Significant sex-related differences exists for muscle fiber type and males have increased musculotendino

us stiffness compared to females which increases the strain energy that is available to these individuals (Blackburn, Padua, Weinhold, & Guskiewicz, 2006; Blackburn, Riemann, Padua, & Guskiewicz, 2004). Additionally, estrogen in females may cause differences in injury rate, differences in pelvic structure and lower extremity may cause differences in training adaptations between male and females (Abe et al., 1998; Chow et al., 2000; Kubo et al., 2003). Thus, it cannot be assumed that all golfers are equally capable of achieving an appropriate level of tissue deformation during the golf swing, or that their tissues possess the same elastic properties (S. J. Brown et al., 2011).

Previous investigators have attempted to identify the sex-related differences on downswing mechanics to determine whether there is an optimal swing mechanic for each sex and/or both sexes to generate and maximise CHS (Table 3). Majority of these investigations have been conducted on highly-skilled and professional (HCP < 5) male and female golfers (Beak et al., 2013; S. J. Brown et al., 2011; Horan et al., 2011; Horan et al., 2010; Horan & Kavanagh, 2012; Myers et al., 2008). The modern golf swing emphasises a restriction on pelvis rotation during the backswing whilst the thorax rotates through a range-of-motion that is approximately double that of the pelvis; producing a coiling effect. The restriction of the pelvis rotation relative to the thorax is based upon the notion that this restriction creates a separation angle between the upper- and lower-body segments and has the potential to increase muscular force and torque generation via a stretch-reflex of the associated musculature and connective tissue (Beak et al., 2013; Horan et al., 2011; Horan & Kavanagh, 2012; Myers et al., 2008). This concept is known as the X-factor stretch and has been shown to increase CHS due to the associated increase in muscular force and torque (Beak et al., 2013; Horan et al., 2011; Horan & Kavanagh, 2012; Myers et al., 2008). In contrast, the classic golf swing emphasise a simultaneous rotation of both the thorax and pelvis during the downswing and therefore, there is an absence of an uncoiling effect and X-factor stretch (Beak et al., 2013; S. J. Brown et al., 2011; Horan et al., 2011; Horan & Kavanagh, 2012; Myers et al., 2008).

Previous investigators indicated several sex-related differences contributing to CHS for highly-skilled male and female golfers (HCP < 5) (Beak et al., 2013; S. J. Brown et al., 2011; Horan et al., 2011; Horan & Kavanagh, 2012; Myers et al., 2008). For example, in male golfers the pelvis leads the thorax segment during the rotation of the downswing to ball contact confirming the utilisation of modern golf swing (*i.e.* the X-factor stretch) to enhance CHS (Table 3) (Beak et al., 2013; Horan & Kavanagh, 2012). In addition, Horan et al. (2011) demonstrated that male golfers have a significantly higher thorax and pelvis coupling ($p < 0.01$, $d = 1.09$) when compared to female golfers which contributes to sex-related differences in CHS. Additionally, during the transition phase (*i.e.* between the top of the backswing to the downswing), male golfers may not require a large amount of axial rotation (*i.e.* thorax = 26˚, pelvis = 41˚) compared to female golfers (*i.e.* thorax = 29˚, pelvis = 50˚) to generate CHS (Horan et al., 2010; Myers et al., 2008). Furthermore, Horton et al. (2001) reported that when the length of professional male golfers' backswing was reduced, there was no significant reduction in CHS despite a 20% decrease in the activation of the trunk musculature (as determined by EMG). Therefore, it is evident that male golfers can generate high amounts of thorax and pelvis angular velocity at ball impact (*i.e.* thorax = 371 to 406 deg/s, pelvis = 434 to 464 deg/s) without a high amount of angular displacement in both segments when compared to female golfers (*i.e.* thorax = 326 ± 82 deg/s) (Horan et al., 2010; Horan & Kavanagh, 2012; Myers et al., 2008). In contrast, when the swing mechanics of female golfers were examined, Brown et al. (2011) reported a moderate relationship between CHS and sitting rotational flexibility of the thorax ($r = 0.71$). The results of this investigation showed the importance of flexibility for generating CHS for female golfers which may be related to anatomical and neuromuscular characteristics affecting the amount of rotation that can be generated for CHS (S. J. Brown et al., 2011; Horan et al., 2011; Horan et al., 2010; Horan & Kavanagh, 2012). The high thorax segment angular velocity for male golfers has also been attributed to the high thorax posterior lateral tilt in the downswing which increases the segmental speed of the golf swing movement pattern (*i.e.* body segments from proximal to distal) (Burden, Grimshaw, & Wallace, 1998; Horan & Kavanagh, 2012; Morgan, 1977). Thus, male golfers produce lateral tilt to generate force and momentum to increase CHS and produce consistent ball striking at ball impact for greater drive distance (Horan et al., 2011; Horan et al., 2010; Horan & Kavanagh, 2012).

Investigators have reported that the angular displacement of upper torso / thorax and pelvis during the backswing does not make a significant contribution to ball speed (Chu et al., 2010; Myers et al., 2008). However, X-factor separation angle in the downswing may contribute to differences in HCP, ball speed and subsequent drive distance (Chu et al., 2010; Myers et al., 2008). When less skilled male golfers (*i.e.* HCP = 15.1 ± 5.2, ball speed = 56 ± 3 m/s [125 ± 7 mph]) and highly-skilled male golfers (*i.e.* HCP = 1.8 ± 3.1, ball speed = 75 ± 4 [168 ± 9 mph]) were compared to determine the amount of X-factor stretch generated, highly-skilled male golfers with high ball speed showed significantly greater torso-pelvic separation angle compared to less skilled golfers with low ball speed (*i.e.* 59 ± 8° vs. 44 ± 8°, respectively) (Myers et al., 2008). Additionally, the torso-pelvic velocity (*i.e.* the speed of uncoiling effect) during the downswing before ball impact showed that highly-skilled male golfers with high ball speeds have significantly greater torso-pelvic velocity (*i.e.* 319 ± 66 deg/s) compared to less skilled golfers with low ball speeds (*i.e.* 205 ± 47 deg/s) (Myers et al., 2008). However, at present, no investigation has examined and compared the torso-pelvis separation angle (*i.e.* X-factor stretch) and velocity of the segments between male and female golfers. Thus, it is uncertain whether female golfers utilise the modern golf swing (*i.e.* X-factor stretch) or classic golf swing (*i.e.* thorax and pelvis movement simultaneously throughout the golf swing) or a hybrid golf swing (*i.e.* combination of both modern and classic golf swing) (Chu et al., 2010; Myers et al., 2008).

To determine changes in golf performance, a number of different measuring devices (*e.g.* Golf simulator, Flightscope launch monitor) are currently available to assess changes in CHS (Alvarez et al., 2012; Bliss et al., 2015; Doan et al., 2006; Fletcher & Hartwell, 2004; Ghigiarelli et al., 2015; Hegedus et al., 2016). However, the Flightscope launch monitor is the only device to have its reliability of CHS reported and published in the literature (ICC = 0.87) (Read, Lloyd, et al., 2013). With advances in recent technology, there are new ways in which rotational velocity of the golf drive performance may be assessed on the golf course and outdoor driving range. For example, an IMU consisting of an accelerometer, gyroscope and magnetometer has been used to measure rotational velocity of the golf club and golf swing motion by placing the devices on the golf shaft (*i.e.* in line with the grip) (Ahmadi et al., 2014; Cao, Suh, & Dang, 2013; Hsu et al., 2016; Nam, Kang, & Suh, 2014; Seaman & McPhee, 2012), the golfer's wrist (Ghasemzadeh, Loseu, & Jafari, 2009), or on the end of the golf club (grip end) (Ueda, Negoro, Kurihara, & Watanabe, 2013). However, there are no reported and/or published studies in the golf literature on the reliability when the IMU is placed on the wrist or club head to measure rotational velocity of the drive performance. Therefore, further research is required to determine the placing of the IMU (*i.e.* wrist or club head) to measure rotational velocity of golf drive performance.

Table 3

Summary of Studies which Examined the Downswing Mechanics of the Golf Drive Performance (*n* = 6)

Reference		Location	Results				
	Sample	Top of backswing to downswing	Angular displacement (deg)	Angular velocity (deg/s)	Axial rotation lateral tilt (deg/s)	CHS	Ball speed
Myers et al. (2008)	n = 100M Age = 45.1+15.9 MHSG HCP = 1.8 ± 3.1 MLSG HCP = 15.1 ± 5.2 BM = 86.5+14.0 Height =1.80+0.07m	Thorax	M = 25.7 ± 8.1	M = 520.1 ± 117.1			
		Pelvis	M = 38.3 ± 7.2	M = 433.6 ± 90.9			
		Torso-pelvis separation (X-factor)		MSG = 319.2 ± 65.6 MLSG = 205.4 ± 47			MLSG = 55.7 ± 2.7 m/s (124.6 ± 6.0 mph) MSG = 75.4 ± 4.4 m/s (168.6 ± 9.84 mph)
Brown et al. (2011)	n = 16F Age = 24.8+7.3 HCP = 1.75+2.35 BM = 65.94+6.23 Height = 1.68+0.06	Pelvis	F = 43.24 ± 8.47				
		Thorax and pelvis coupling		F= 134.12 ± 79.4		F = 39.48 ± 2.48 m/s (88.31 ± 5.54 mph)	
Horan et al. (2010)	n = 19M Age = 26 ± 7 HCP = 0.6 ± 1.1 BM = 80.2 ± 9.1 Height = 1.80 ± 0.05 n = 19F Age = 25 ± 7 HCP = 1.3 ± 1.6 BM = 62.2 ± 9.6 Height = 1.67 ± 0.06	Thorax	M= 25.2 ± 8.9 F= 29.3 ± 11*	M = 371 ± 82 F = 326 ± 82*			
		Pelvis	M = 43.6 ± 11.9 F = 49.6 ± 11.9*		M = 107 ± 49 F = 69 ± 38*	M = 49.1 ± 3.6 m/s (49.1 ± 8.05 mph) F = 40.4 ± 3.0* m/s (90.37 ± 6.71 mph)	

Table 3

Continued

Horan et al. (2011)	n = 19M Age = 26 ± 7 HCP = 0.6 ± 1.1	Thorax	F > M (p = 0.02, d=0.81)				
	BM = 80.2 ± 9.1 Height = 1.80 ± 0.05	Pelvis	F > M (p = 0.04, d = 0.66)				
	n = 19F Age = 25 ± 7 HCP = 1.3 ± 1.6	Thorax and pelvis coupling		F are lower than M (p < 0.01, d = 1.09)	F are lower than M (p < 0.01, d = 1.01)		
	BM = 62.2 ± 9.6 Height = 1.67 ± 0.06					M = 49.1 ± 3.6 m/s (49.1 ± 8.0 mph) F = 40.4 ± 3.0 (P <0.01)	M = 69.5 ± 5.2 m/s (155.46 ± 11.6 mph) F = 57.2 ± 4.2 (p<0.01)
Horan & Kavanagh, (2012)	n = 14M Age = 27 ± 8	Thorax		M = 491 ± 54	M = 406 ± 50		
	HCP = Pro BM = 81.2 ± 9.6	Pelvis		M = 464 ± 46	M = 188 ± 52		
	Height = 1.79 ± 0.04	Thorax and pelvis coupling		M R^2 = 0.98 ± 0.01 Phasing = 4 ± 5	M R^2 = 0.91 ± 0.10 Phasing = -2 ± 3		
						M = 50.1 ± 2.1 m/s (112.1 ± 4.7 mph)	
Beak et al. (2013)	n = 14M Age = 29 ± 8 HCP = 0	Thorax and pelvis coupling		M R^2 = 0.97 ± 0.02 Phasing = 11 ± 18	M R^2= 0.75 ± 0.16 Phasing = 26 ± 18		
	BM = 74.6 ± 9.3 Height = 1.76 ± 7.9					M = 45.4 ± 3.9 m/s (101.5 ± 8.7 mph)	M = 70.6 ± 4.2 m/s (157.9 ± 9.4 mph)

Key: Statistically significant p ≤ 0.05*. Age = years old; BM = body mass in kilogram; d = cohen's D effect size; F = female; HCP = handicap; Height = in metres; M = male, Max = maximum; MHSG = male highly-skilled golfers; MLSG = male less skilled golfers; n = number of participants; Pro = professional golfers.

2.6 Golf Resistance Training Programme

The golf swing is a high-velocity rotational movement requiring golfers to possess explosive power to maximise drive distance (Farrally et al., 2003; Schofield, 2015; Smith, Callister, & Lubans, 2011). Increases (1.20 to 10.00 m/s [2.68 to 22.36 mph]) (Alvarez et al., 2012; Chen et al., 2010; Doan et al., 2006; Kim, 2010; Lephart et al., 2007; Thompson et al., 2007; Weston et al., 2013) and decreases (0.89 to 1.96 m/s [1.99 to 4.38 mph])) (Lamberth et al., 2013; Loock et al., 2012) in CHS have been reported following different resistance training protocols (*i.e.* hypertrophy, flexibility, rehabilitative, functional movement, strength, ballistic and plyometric protocols). Despite the contrasting results with regards to changes in CHS, golf-specific resistance training programmes (*i.e.* exercises with similar movement patterns, swing kinematic sequences, movement velocities, and/or body positions as the golf swing) that are designed to improve drive distance have consistently produced significant improvements in strength, power and CHS for male golfers (Alvarez et al., 2012; Bliss et al., 2015; Chen et al., 2010; Lephart et al., 2007; Thompson et al., 2007; Weston et al., 2013). However, only four studies have addressed the effects of such resistance training programmes in female golfers (Doan et al., 2006; Hegedus et al., 2016; Hetu & Christie, 1998; Kim, 2010).

2.6.1 Golf resistance training protocols. The inclusion of golf-specific exercises has been shown to improve golf drive performance and neuromuscular characteristics of golfers (*i.e.* HCP = 0-18) (Alvarez et al., 2012; Bliss et al., 2015; Doan et al., 2006; Lephart et al., 2007). To transfer the training induced adaptations to movements associated with the golf swing, the principle of training specificity must be adhered to when prescribing exercises for golfers (Bliss et al., 2015; Hume et al., 2005; Keogh et al., 2009; Sell et al., 2007). Previous investigators have reported increases in CHS when incorporating either golf-specific exercises that are performed in similar movement plane to the golf swing or are high velocity in nature (*e.g.* side medicine ball rotational throws, weighted golf club swings, resisted golf swings) (Alvarez et al., 2012; Bliss et al., 2015; Doan et al., 2006; Lephart et al., 2007) (Table 4 and 5). For example, Alvarez et al. (2012) prescribed an 18-week periodised training programme consisting of six-week of maximal strength training, six-week of complex training (*i.e.* maximal strength training combined with plyometric exercises) and six-week of golf-specific training (*i.*e. ballistic exercises) for skilled male golfers (HCP ≤ 10, ≤ 30 years old, with previous resistance training experience). Following the training intervention, the participants increased their club head acceleration by 1.8% while the control group increased their club head acceleration by 0.7% ($p<0.05$). In comparison, Hegedus et al. (2016) prescribed traditional strength training (*i.e.* unidirectional exercises) compared with golf strengthening resistance training (*i.e.* dynamic movement and multi-plane resistance) and reported non-significant difference between the improvements (*i.e*. 2.47% increase by traditional strength training vs 1.98% increase by golf strengthening resistance training group) in CHS for older less skilled female golfers (HCP ≥ 11, age > 30, without previous resistance training experience). It was concluded that the golf strengthening resistance training programme lacked movement specificity as the study did not incorporate and/or progress the strength exercises to golf-specific ballistic exercises which may have contributed to the non-significant difference in CHS (Hegedus et al., 2016). Golf-specific exercises may enhance the intra- and inter-muscular co-ordination of swing movement patterns which may in turn contribute to increased rotational power by means of improved velocity and/or force-related components during the golf swing (Smith et al., 2011). Thus, to improve CHS in the golf drive, the exercises in the training programme require training velocities and/or movement patterns similar to the golf swing to produce greater rotational power. However, if the golf-specific exercises are performed with poor technique, there is also a potential concern that they may disrupt the player's swing mechanics (Bliss et al., 2015; Hume et al., 2005; Keogh et al., 2009; Sell et al., 2007; Smith et al., 2011).

Decreases in CHS (0.89-1.96 m/s [1.99 to 4.38 mph]) have been reported following non-golf-specific training protocols such as hypertrophy-based resistance training interventions due to negative changes in flexibility (Lamberth et al., 2013; Loock et al., 2012). The resulting decrease in the participants' range-of-motion may have contributed to increased swing variability may be due to a disruption in the segmental sequencing of the golf swing movement patterns along with a decrease in X-factor stretch (Lamberth et al., 2013; Loock et al., 2012). Additionally, Loock et al. (2012) showed a non-significant decrease in CHS (0.89 m/s) following a 12-week CorePower machine training programme that focused on solely training the core musculature. The CorePower machine consists of a rowing motion performed by the upper-extremities and stepping motion performed by the lower-extremities. Although previous golf EMG muscle activation studies indicated the importance of core musculature throughout the phases of the golf swing (Aggarwal et al., 2008; Watkins et al., 1996), the reported decrease in CHS was possibly due to the low training volume and lack of golf movement specificity (Loock et al., 2012). Collectively, the evidence suggests that it is difficult to increase CHS by solely training through a sagittal plane and/or general hypertrophy exercises because the golf swing requires explosive rotational movements performed with similar velocities to the golf swing and/or in similar movement plane (Baechle & Earle, 2008; Lamberth et al., 2013; Loock et al., 2012). However, Weston et al. (2013) showed an increase in CHS (1.2 m/s) by using isometric, general core exercises in an eight-week core training programme. These findings may have been due to the cohorts' characteristics which included less skilled golfers with HCP ≥ 11, who had no resistance training experience and were aged >30 years old (Weston et al., 2013).

Methodology and participants' characteristics (*i.e.* resistance training experience, golf skill level and biological age) may account for the differences in CHS results. Golfers who are older (aged >30 years old) and/or less skilled (HCP ≥ 11) have demonstrated improvements in CHS following functional, rehabilitative, strength, flexibility and/or golf-specific exercises (*i.e.* resisted golf swings) (Lephart et al., 2007; Thompson et al., 2007; Weston et al., 2013). The use of low-intensity, slow movement exercises in the majority of the training programmes may have limited the possible training-induced increases in CHS (Lephart et al., 2007; Thompson et al., 2007; Weston et al., 2013). However, two such studies progressively incorporated golf-specific ballistic type exercises for two to three weeks prior to the end of the training programme to ensure the participants established adequate neuromuscular control and dynamic strength in the core musculature prior to performing rotational exercises at maximal speed (Lephart et al., 2007; Thompson et al., 2007). Professional (HCP = 0), highly-skilled (HCP < 5) and skilled golfers (HCP

≤ 10) have refined and efficient swing mechanics, therefore improvements in CHS following golf-specific resistance training programmes was subsequently caused by improvements in muscle morphology, kinetics and kinematics which improved their rotational power ability (Alvarez et al., 2012). However, less skilled golfers (HCP of ≥ 11) typically have less efficient swing mechanics (possibly due to increased swing variability) and therefore the improvements in CHS may be the combined result of changes in swing mechanics muscle morphology, kinetics and kinematics (Hegedus et al., 2016; Lephart et al., 2007; Thompson et al., 2007).

Ballistic training (*i.e.* side rotational throws and chest throws) focuses on high velocities that emphasise concentric (shortening of the muscle) acceleration (Fletcher & Hartwell, 2004). The golf drive motion can be classified as a ballistic action (*i.e.* stretch shortening movement) due to the limited transition time between the eccentric (backswing) and concentric (downswing) action (Bliss et al., 2015; Fletcher & Hartwell, 2004) (Bliss et al., 2015; Fletcher & Hartwell; 2004). Previous investigators have reported improvements in ballistic and plyometric measures (*i.e.* upper- and lower-body power) which contribute to improvements in CHS following golf-specific resistance training interventions (Table 4 and 5) (Alvarez et al., 2012; Bliss et al., 2015; Doan et al., 2006; Lephart et al., 2007). Improvements in pre-to-post measures of upper- and lower-body power following ballistic and plyometric training can positively influence the swing mechanics of participants (Ghigiarelli et al., 2015; Lephart et al., 2007). Furthermore, previous authors of studies have reported significant increases in upper torso and pelvis axial rotational velocity during the downswing and increases in X-factor velocity (rate of change in X-factor) for male golfers post training (Ghigiarelli et al., 2015; Lephart et al., 2007). Therefore, the greater utilisation of the X-factor stretch, and subsequent uncoiling effect may possibly be due to a greater change in the length of the associated musculature and tendon tissues (Ghigiarelli et al., 2015; Lephart et al., 2007). This form of elastic deformation may result in a greater amount of strain energy and increase in CHS for male golfers (Ghigiarelli et al., 2015; Lephart et al., 2007). Due to gender difference in anatomy and neuromuscular profiles it cannot be assumed that the increases in CHS following ballistic training in males (Bliss et al., 2015; Ghigiarelli et al., 2015) would also be observed for female golfers. At present, no investigations have prescribed golf-specific ballistic training for female golfers and this is an area requiring further research.

Table 4

Summary of Golf Training Programmes on Golf Drive Performance (*n* = 16)

Study	Study design	Sample	Programme Protocol	General Exercise	Target muscles for training	Golf drive performance results	3D biomechanics analysis in golf swing
Hetu et al. (1998)	Training intervention (no control group)	n = 12M and 5F Age = 52.4 ± 6.7 HCP = N/A BM = N/A Height = N/A	8-week strength, flexibility and plyometric training.	Barbells, dumbbells and body weight exercises (medicine ball and foam ball).	DNS	CHS ↑ 1.36m/s* (3.0mph)	N/A
Fletcher & Hartwell, (2004)	Control Trial	n =11M, Age = 29 ± 7.4 HCP = 5.5 ± 3.7 BM = 76.6 ± 6.8 Height = 179.3 ± 5.4	8-week combined strength and plyometric training.	Free weight exercises, ballistic medicine ball rotations, throws, and jumps.	DNS	CHS ↑ 1.5m/s* (3.3 mph)	N/A
Fradkin et al. (2004)	Experimental and Control trial	n = 1M, Age = 39.6 HCP = 19.6 BM = N/A Height = N/A	5-week flexibility training.	Static and dynamic stretching, and golf resisted swings.	DNS	CHS ↑ 7-10 m/s* (15.6-22.4 mph)	N/A
Thompson & Osness, (2004)	Experimental and Control trial	Exp: n = 19M Age = 64.3 ± 6.2 BM = 81.2 ± 3.2 Height = 177.5 ± 6.6 Con: n = 12M Age = 66.2 ± 5.9 BM = 83.0 ± 2.7 Height = 178.3 ± 6.2 HCP = N/A	8-week strength and flexibility training.	Machine based full body conditioning exercises, weighted golf club swings and stretching.	DNS	CHS ↑ 0.94m/s* (2.1 mph)	N/A

Table 4
Continued

Doan et al. (2006)	Longitudinal training intervention (no control group)	n = 10M and 6F Age (M) = 19.8 ± 1.7 Age (F) = 18.5 ± 0.8 HCP (M) = 0 HCP (F) = 5-10 BM (M) = 74.5 ± 9.0 BM (F) = 63.5 ± 4.1 Height (M) = 178.8 ± 5.6 and (F) = 169.5 ± 3.9	11-week strength and conditioning training.	Traditional resistance training (bench press, leg curl, squat, dumbbell) and ballistic medicine ball rotational exercise.	DNS	CHS ↑ 0.76m/s* (1.7mph)	N/A
Lephart et al. (2007)	Training intervention One group pre/post-test design	n = 15M Age = 47.2 ± 11.4 HCP = 12.1 ± 6.4 BM = 86.7 ± 9.0 Height = 178.8 ± 5.8	8-week conditioning training.	Rehabilitation movements, ballistic exercises and resisted golf swings.	Lower-body (hip strength and flexibility) and upper-body (torso and shoulder rotation, flexibility and strength).	CHS ↑ 2.3 m/s* (5.1 mph)	During the downswing in the acceleration phase: ↑ 7%* Upper torso axial rotation, ↑ 2.8% Pelvis axial rotation, ↑ 14% X-factor.
Thompson et al. (2007)	Control Trial	n = 18M Age = 70.7 ± 7.1 HCP = N/A BM = N/A Height = N/A	8-week progressive functional training.	Functional body weight exercises to medicine ball ballistic exercises.	Calves, hamstrings, quadriceps, hip flexors, gluteus maximus, latissimus dorsi, rhomboids, deltoids, triceps, and levator scapulae.	CHS ↑ 4.9 m/s* (10.9 mph)	N/A

Table 4
Continued

Chen et al. (2010)	Case study	n = 1M Age = 19 HCP = 10 BM = 78.47 Height = 155.48	3-week correctional resistance training and flexibility.	Resistance band exercises and vibration training.	Shoulder (anterior deltoid, levator scapulae, pectoralis major), thoracic region and neck.	CHS ↑ 4 m/s* (8.9 mph)	N/A
Kim, (2010)	Control Trial	Exp: n = 9F Con: n =8F HCP = LPGA Age = 22.9 ± 3.69 BM = 59.07 ± 6.19 Height = 164.55± 5.03	12-week combined lower limb/core training.	Traditional resistance training (deadlift, squat, crunch, back extensions) and ballistic medicine ball rotational exercises.	DNS	CHS ↑ 1.35m/s* (3.02 mph)	N/A
Alvarez et al. (2012)	Control trial	Exp: n = 5 Age = 24.2 ± 5.4 HCP = 2.1 ± 2.3 BM = 68.09 ± 8.3 Height = 171.9 ± 7 Con: n = 5 Age = 23.9 ± 6.7 HCP = 1.6 ± 1.1 BM = 70.76 ± 7.1 Height = 172.1 ± 4	18-week periodised training.	Full body maximal strength exercises and progress to combined strength and plyometric exercises. Followed by, ballistic exercises.	Deltoids, rectus abdominus, biceps, triceps, latissimus dorsi, external oblique, quadriceps, gluteus maximus, hamstrings, gastrocnemius, soleus and forearm muscles.	Club head acceleration ↑ 17.6m/s^2	N/A
Loock et al. (2012)	Pilot study	n = 9M Age = 17-76 HCP = 10.56 BM = N/A Height = N/A	12-week core power machine training.	Corepower' machine (row mechanism performed by the upper extremities and step mechanism performed by the lower extremities).	Core musculature	CHS ↓ 0.89 m/s (1.99 mph)	N/A

Table 4
Continued

Lamberth et al. (2013)	Experimental and Control trial	n = 10M, Age = 21.4 ± 2.3 HCP = < 8 BM = N/A Height = N/A	6-week hypertrophic training.	Compound, cable, free weight and machine exercises.	DNS	CHS ↓ 1.96m/s (4.38 mph)	N/A
Weston et al. (2013)	Experimental and control trial	n = 36M Age = 47 ± 12 HCP = 11.2 ± 6.1 BM = 89 ± 15 Height = 180.8 ± 6.8	8-week core training.	Isometric and dynamic body weight movement.	Core muscles (multifidus, oblique, gluteus medius, gluteus maximus, abdominal external oblique muscles, vastus medialis)	CHS ↑ 1.2 m/s (2.7 mph)	N/A
Bliss et al. (2015)	Experimental and Control trial	Exp: n = 8M Age = 17.3 ± 1.5 BM = 68.0 ± 7.6 HCP = 4.7 ± 3.0 Height = 173 ± 0.9 Con: n = 8M Age = 17.4 ± 0.9 BM = 74.3 ± 10.8 HCP = 5.2 ± 2.5 Height = 174 ± 0.9	8-week golf-specific plyometric training.	Golf-specific ballistic exercises (side rotational throws) and plyometric jumps (CMJ, SJ, board jump and single leg bounds).	DNS	CHS ↑ 0.8 m/s (1.78 mph)	N/A

Table 4
Continued

Ghigiarelli et al. (2016)	Case study	n = 1M Age = 42 HCP = 25 BM = N/A Height = N/A	14-week golf-specific training program.	Pelvic rotational velocity, upper- and lower-body strength and dynamic mobility. Multi-joint dynamic exercises that are explosive movements in transverse plane.	DNS	↓ Swing tempo (pace of the golf swing) 9.8% between week 1 and 8	↑ Pelvic rotational velocity 6%* and 9%* deg/s between week 1 to 8 and week 8 to 9 respectively. ↑ Torso rotational velocity 4.6%* on week 8 to 14.
Hegedus et al. (2016)	Control trial	TRAD: n = 15F Age = 58.5 ± 2.1 HCP = 22 ± 6.3 BM = 72.8 ± 4.1 Height = 164.7 ± 1.3 GSRT: n = 14F Age = 57.6 ± 3.7 HCP = 14 ± 8.2 BM = 66.8 ± 4.7 Height = 161 ± 1.8	10-week TRAD compared GSRT golf performance.	TRAD: strengthening exercises unidirectional resistance with stability. GSRT: strengthening exercises, dynamic movement, balance, stability, and multi-plane resistance.	Erector spinae, abdominal oblique, pectoralis major, latissimus dorsi, levator scapulae, rhomboids, gluteus muscles, hamstrings, and wrist flexors.	Adjusted mean differences (within group) TRAD: ↑ CHS 1.4 ± 0.5 m/s (3.1 ± 1.11 mph) (95% CI = 0.3, 2.6) GSRT: ↑ CHS 1.3 ± 0.6 m/s (2.9 ± 1.3 mph), (95% CI = 0.1, 2.4)	N/A

Key: statistically significant p ≤ 0.05*. Age = years old, BS = ball speed; BM = body mass in kg; CHS = club head speed; CI = confident interval; DNS = did not state; Exp = Experimental; F = female; GSRT = golf-specific resistance training; HCP = handicap; Height = in centimeters; LPGA = ladies professional golfers association; M = male; N/A = not available; n = number of participants; 1RM = One-repetition maximum; STR = strength.

2.6.2 The changes in neuromuscular characteristics after golf resistance training programme. When strength and flexibility (*i.e.* torso, shoulder and hip rotation) training are combined, the increase in range-of-motion helps to facilitate improvements in CHS (Doan et al., 2006; Hetu & Christie, 1998; Kim, 2010; Lephart et al., 2007; Thompson et al., 2007; Thompson & Osness, 2004). In contrast, Lamberth et al. (2013) reported significant increases (8-11%) in leg and chest strength for male golfers but their improvements in neuromuscular performance did not transfer to improvements in CHS (non-significant decrease 1.96 m/s). The lack of training transference is likely due to the hypertrophic exercises that were used as opposed to golf-specific movements. Hypertrophic exercises (*i.e.* performed in slow movement speed in non-golf-specific movement planes) may have increased muscle cross-sectional area but may not have improved the required qualities of the muscle fibers themselves (*i.e.* a lack of fast twitch muscle fibre adaptation). Therefore, it is important to incorporate golf-specific exercises in training programmes to improve CHS and to also incorporate measurements that assess the neuromuscular characteristics required in the golf swing (*e.g.* upper-body rotational measurements) (Table 5) (Alvarez et al., 2012; Doan et al., 2006; Hegedus et al., 2016).

The majority of studies that assessed flexibility following resistance training interventions have shown improvements in right/trail side (7.3-32%) and left/lead side (9.6-21% torso rotation (Chen et al., 2010; Doan et al., 2006; Thompson et al., 2007; Thompson & Osness, 2004), total trunk rotation (18.7–47.3%) (Hetu & Christie, 1998; Thompson & Osness, 2004), and hip rotation (internal 1.5%, external 19.8% deg) (Thompson & Osness, 2004) in right handed golfers (Table 5). It is speculated that increases in flexibility may improve both the modern golf swing (*i.e.* via an increase in X-factor stretch, coiling and uncoiling effect) and the classic golf swing (*i.e.* via a greater rotation of torso or trunk and hip rotation) which is beneficial for golfers of all skill levels and gender (Chen et al., 2010; Doan et al., 2006; Hetu & Christie, 1998; Thompson et al., 2007; Thompson & Osness, 2004). However, changes in swing mechanics were not assessed in these previous investigations so it is uncertain to what degree flexibility training influenced swing mechanics and CHS.

All investigators that have prescribed high-velocity based exercises as part of their golf-specific resistance training intervention have reported improvements in ballistic (*e.g.* medicine ball seated throws and total body medicine ball side rotational throws) and plyometric (*e.g.* countermovement jump [CMJ] and squat jump [SJ]) measures of power (Table 4 and 5) (Alvarez et al., 2012; Bliss et al., 2015; Doan et al., 2006; Hegedus et al., 2016; Lephart et al., 2007). A previous investigation focused on ballistic and plyometric exercises and found a statistically significant improvement in all upper- and lower-body power measures (*i.e.* standing vertical jump, standing board jump, kneeling rotational throw and kneeling chest throw) and CHS without inclusion of strength and/or flexibility exercises for male golfers (Bliss et al., 2015). Therefore, lower-body plyometric exercises that emphasis on short ground contact time and stretch shortening cycle (SSC) contribute to improvement in CHS. The greatest improvement was seen in kneeling rotation throws (*i.e.* 22.9%; utilisation of upper-body rotation); thus upper-body power and rotational velocity may play a greater role in the production of CHS in comparison to the lower-extremities

(Bliss et al., 2015). Consequently, improvements in upper-body power (*i.e.* velocity component) may increase the SSC and elastic energy production which improves CHS for male golfers (Alvarez et al., 2012; Bliss et al., 2015; Fletcher & Hartwell, 2004). In contrast, for female golfers, it is possible that the golf swing requires a slower SSC allowing an increase in time for cross-bridge formation during the backswing to generate high CHS (Hegedus et al., 2016). Therefore, a gap in the literature currently exists as no investigations have assessed the effects of ballistic and plyometric training on female golfers, without the inclusion of functional movement, strength and/or flexibility exercises.

Table 5

Changes in Neuromuscular Characteristics Post Golf Resistance Training Programme (*n* = 14)

Study	Study design	Sample	Programme Protocol	Strength	Ballistic and plyometric measures of power	Flexibility/Mobility	Relationship between neuromuscular and golf performance tests
Hetu et al. (1998)	Training intervention (no control group)	n = 12M and 5F Age = 52.4 ± 6.7 HCP = N/A BM = N/A Height = N/A	8-week strength, flexibility and plyometric training.	Leg extension ↑ 18.1%* Chest press ↑ 14.2%* Grip strength ↑ 6.2%*	N/A	Sit and reach ↑ 39.9%* Trunk rotation ↑ 47.3%*	N/A
Fletcher & Hartwell, (2004)	Control Trial	n =11M Age = 29 ± 7.4 HCP = 5.5 ± 3.7 BM = 76.6 ± 6.8 Height = 179.3 ± 5.4	8-week combined strength and plyometric training.	Upper-body strength arm curl test (reps): 19.5 ± 6.6 to 23.9 ± 6.6 Lower-body strength 30-second chair stand test (reps): 16.1 ± 6.0 to 18.0 ± 6.7*	N/A	N/A	N/A

Table 5
Continued

Thompson & Osness, (2004)	Experimental and Control trial	Exp: n = 19 Con: n = 12 Exp: Age = 64.3 ± 6.2 Con: Age = 66.2 ± 5.9 HCP = N/A Exp: BM = 81.2 ± 3.2 Con: BM = 83.0 ± 2.7 Exp: Height = 177.5 ± 6.6 Con: Height = 178.3 ± 6.	8-week strength and flexibility training.	Exp: Chest press ↑ 35.6%* Abdominal curl ↑ 28.9%* Shoulder press ↑ 38.3%* Lat pull down ↑ 21.3%* Leg curl ↑ 27.3%* Leg press ↑ 41.1%* Leg extension ↑ 38.5*	N/A	Exp: Trunk rotation ↑ 18.7%* Internal shoulder rotation ↑ 24.2%* External shoulder rotation ↑ 18.2%* Internal hip rotation ↑ 1.5% External hip rotation ↑ 19.8%	N/A
Doan et al. (2006)	Longitudinal training intervention (no control group)	n = 10M and 6F Age (M) = 19.8 ± 1.7 Age (F) = 18.5 ± 0.8 HCP (M) = 0 HCP (F) = 5-10 BM (M) = 74.5 ± 9.0 BM (F) = 63.5 ± 4.1 Height (M) = 178.8 ± 5.6 Height (F) = 169.5 ± 3.9	11-week strength and conditioning intervention.	Bench press 1RM ↑ 10.18% Squat 1 RM ↑ 13.27%* ((estimated from 4–6 RM) Lat pull 1 RM ↑ 12.61%* (estimated from 6–10 RM) Shoulder press 1 RM ↑ 23.56% Grip strength ↑ 7.29%	N/A	Trunk rotation flexibility backswing ↑ 14.82%* Trunk rotation downswing ↑ 9.71%*	N/A

Table 5
Continued

Lephart et al. (2007)	Training intervention One group pre/post-test design	n = 15M Age = 47.2 ± 11.4 HCP = 12.1 ± 6.4, BM = 86.7 ± 9.0 Height = 178.8 ± 5.8	8-week conditioning exercises.	Bench press (1-RM) ↑ 82.08 ± 9.38 to 89.34 ± 10.34* (kg) Leg press ↑ 94.81 ± 16.62 to 103.86 ± 18.44* (kg)	Vertical jump ↑ 85.9 ± 8.2 to 87.5 ± 9.7 (cm)	Sit-and-reach test ↓ 41.15 ± 2.04 to 43.67 ± 7.87 (cm)	N/A
Thompson et al. (2007)	Control Trial	n = 18M Age = 70.7 ± 7.1 HCP = N/A BM = N/A Height = N/A	8-week progressive functional training programme.	Biodex % change: ↑ 13.3* right torso rotation ↑ 8.9* left torso rotation ↑ 8.6* abduction ↑ 9.9* isometric right hip abduction	N/A	Left torso axial rotation ↑ 9.6%* Right torso axial rotation ↑ 7.3%* Left hip flexion ↑ 7.4%* Left hip extension ↑ 36%* Right hip flexion ↑ 7.4% Hip extension ↑ 38.4%*	N/A

Table 5
Continued

Chen et al. (2010)	Case study	n = 1M Age = 19 HCP = 10 BM = N/A Height = 155.48	3-week correctional resistance training and flexibility.	N/A	N/A	Head-alignment at the top of the golf swing ↑ 11 (deg) Left torso rotation ↑ 21 (deg) Right torso rotation ↑ 32 (deg) Horizontal shoulder extension ↑ 4 (cm) Shoulder flexion ↑ 5 (cm)	N/A
Kim, (2010)	Control Trial	Exp: n = 9F Con: n = 8F Age = 22.9 ±3.69 HCP = LPGA BM = 59.07+6.19 Height = 164.55± 5.03	12-week combined lower limb/core training.	Isotonic back extension ↑ 16.62 ± 4.06 to 25.87 ± 3.97* (kg) Isotonic squat ↑ 81.25 ± 12.55 to 96.24 ± 15.55* (kg) Isometric lower back strength ↑ 89.75 ± 11.83 to 100.06 ± 16.98 (kg)		Forward flexion ↑ 18.61 ± 3.53 to 20.28 ± 3.96* (cm) Back flexion ↑ 54.36 ± 54.36 to 59.46 ± 5.76* (cm)	N/A

Table 5
Continued

Alvarez et al. (2012)	Control trial	Exp: n = 5 Age = 24.2 ± 5.4, HCP = 2.1 ± 2.3, BM = 68.09 ± 8.3 Height = 171.9 ± 7 Con: n = 5 Age = 23.9 ± 6.7 HCP = 1.6 ± 1.1 BM = 70.76 ± 7.1kg Height =172.1 ± 4	18-week strength training program on golfers' performance	Horizontal bench press (1-RM) ↑ 55.24 ± 10.48 to 60.30 ± 19.27b* (kg) Barbell squat (1-RM) ↑ 131.30 ± 30.31 to 166.18 ± 23.94* (kg), Barbell military press (1-RM) ↑ 40.98 ± 16.94 to 47.72 ± 16.28b* (kg)	SJ ↑ 33.40 ± 1.47 to 36.28 ± 0.88 (cm) CMJ ↑ 35.55 ± 1.66 to 38.08 ± 2.14 (cm)	N/A	N/A
Loock et al. (2012)	Pilot study	n = 9M Age = 17-76 HCP = 10.56 BM = N/A Height = N/A	12-week core power machine.	Wall squat ↑ 10.89% Hand Grip Strength ↓ -0.23%		Lower back flexibility ↑ 6.27%*	N/A
Lamberth et al. (2013)	Experimental and Control trial	n = 10M Age = 21.4 ± 2.3 HCP = 8 BM = N/A Height = N/A	6-week hypertrophic intervention.	N/A	N/A	N/A	N/A
Weston et al. (2013)	Experimental and control trial	n = 36M Age = 47 ± 12 HCP = 11.2 BM = 89 ± 15 Height = 180.8 ± 6.8	8-week core training (isolated).	Core endurance test: 91 ± 56 (seconds)	N/A	N/A	N/A

Table 5
Continued

Bliss et al. (2015)	Experimental and Control trial	Exp: n = 8 Age = 17.3 ± 1.5 BM = 68.0 ± 7.6 HCP = 4.7 ± 3.0 Height =173 ± 0.9 Con: n = 8 Age = 17.4 ± 0.9 BM = 74.3 ± 10.8 HCP = 5.2 ± 2.5 Height =174 ± 0.9	8-week golf-specific plyometric training.	N/A	SVJ ↑10.8%* SBJ ↑ 10.2%* KCT ↑ 11.1%* KRT ↑ 22.9%*	N/A	N/A
Hegedus et al. (2016)	Control trial	TRAD: n = 15F Age = 58.5 ± 2.1 HCP = 22 ± 6.3 BM = 72.8 ± 4.1 Height = 164.7 ± 1.3 GSRT: n = 14F Age = 57.6 ± 3.7 HCP = 14 ± 8.2 BM = 66.8 ± 4.7 Height = 161 ± 1.8	10-week TRAD compared GSRT on golf performance.	N/A	N/A	N/A	Seated weighted ball throw was selected first (r^2 = 0.384; 95% CI [0.160, 0.608]) Broad jump (r^2 = 0.446, CI [0.234, 0.658])

Key: statistically significant p ≤ 0.05*. Age = years old; BM = body mass in kilograms; CHS = club head speed; CI = confident interval; CMJ = countermovement jump; Exp = experimental; F = female; GSRT = golf-specific resistance training; HCP = handicap; Height = in centimeters; KCT = kneeling chest throw; KRT = kneeling rotational throw; LPGA = ladies professional golfers association; M male; N/A = not available; n = number of participants; 1RM = One-repetition maximum; SJ = squat jump; SBJ = standing board jump; SVJ = standing vertical jump; TRAD = traditional resistance training.

2.7 Practical Implications

It is important for golf practitioners to understand the sex-related differences in swing mechanics (*i.e.* angular displacement and velocity, X factor stretch) and adaptations to resistance training programmes (*i.e.* muscle fibre type, musculotendinous stiffness and muscle tissue elastic properties) when determining training type prescription. When designing golf-specific resistance training programmes, practitioners should consider the participant's gender, biological age, resistance training experience, and golf skill level. Training programmes for less skilled golfers (HCP ≥ 11) and/or those without resistance training experience should focus on strength and flexibility exercises. Golf-specific ballistic and plyometric exercises can be progressively incorporated over time for less skilled golfers and/or those without resistance training experience. However, training programmes for professional (HCP = 0), highly-skilled (HCP < 5) and skilled golfers (HCP ≤ 10) and/or those with resistance training experience should incorporate power type resistance training consisting of golf-specific ballistic (*e.g.* side medicine ball rotations, resisted golf swings, weighted golf club swings) and plyometric (*e.g.* CMJ and SJ) exercises to improve neuromuscular characteristics for drive performance (CHS).

2.8 Recommendation for Future Studies

Future investigations are required to determine the sex-related differences in the muscle activation of the thorax and pelvis regions during the golf swing for golfers with various skill level/HCP with reference to the swing type adopted by the participants. Furthermore, at present there are no studies that have examined the torso-pelvis separation angle and velocity of the segments in the golf swing for female golfers. These findings may provide further understanding of which muscles are required to produce high CHS to improve drive performance in male and/or female golfers of various skill levels (*i.e.* professional, highly-skilled, skilled and less skilled).

Swing kinematics should also be measured pre-to post resistance training to determine the changes in swing mechanics (*i.e*. X-factor stretch, torso and pelvis rotational displacement and velocity). The assessment of swing mechanics (*i.e.* 3D golf biomechanical analysis) may determine if meaningful changes in swing mechanics have occurred which can provide a better understanding of the effects of a training intervention on neuromuscular characteristics and golf drive performance. Additionally, there are currently no published studies on the reliability and validity of placing field-based equipment (IMU) on the lead wrist and/or golf shaft to determine rotational velocity of the upper extremities and/or golf club. Field based measures (*e.g.* IMU) are important to enable assessment of changes in golf drive swing mechanics.

Furthermore, a gap exists in the golf literature on resistance training for female golfers as no studies have examined the effects of ballistic and plyometric training on female golfers' drive performance and neuromuscular characteristics. Further research on female golfers may allow a better understanding of female golfers' adaptations to ballistic and plyometric training and determine whether there are indeed sex-related differences.

2.9 Conclusion

The downswing is the most important phase of the golf swing to produce high CHS for maximal drive distance. Sex-related differences in the biomechanics of the downswing can cause variations in CHS and ball speed for drive performance. Differences in study methodologies, such as participant characteristics, training protocols and exercises, make it difficult to compare multiple studies on golf resistance training. However, the majority of training studies have shown improvements in CHS after golf resistance training programmes for male and female golfers. The inclusion of golf-specific exercises can elicit further improvements in CHS following resistance training as they activate the muscle groups required in the golf swing in a similar temporal fashion. The possible reasons for a decrease in CHS following training interventions are a lack of golf-specific exercises, decreases in the neuromuscular characteristics of the golfer, negative changes in swing mechanics and/or an increase in endpoint movement variability. When designing research on a golf-specific resistance training programme, the participants' characteristics (*i.e.* biological age, gender, HCP, golf swing mechanics, and resistance training experiences) needs to be considered to determine the type of training programme to develop and improve in neuromuscular characteristics and drive performance.

Chapter Three:

The reliability of an inertial measurement unit to measure the rotational velocity of a golf drive

3.1 Preface

Field-based equipment (*i.e.* Flightscope launch monitor and Trackman) have previously been used in scientific research to measure golf club head, shaft and ball speed. Previous investigators have also attached IMU on the golf shaft and/or on the end of the club (grip end) to measure multi-segmental rotational velocities during a single swing. However, at present there is a gap in the literature where no studies that have measured the reliability of field-based equipment (*i.e.* IMU) to measure rotational velocity of the golf swing. Therefore, the purpose of this study was to determine the reliability of the IMU device to assess rotational velocity of the golf swing when placed on the lead wrist.

3.2 Introduction

The ability to create rotational velocity more efficiently is essential to maximise rotational power and CHS which will contribute to overall improvements in drive performance (S. J. Brown et al., 2011; Chu et al., 2010; Okuda et al., 2010). An abundance of researchers have investigated the biomechanics of the golf swing using three-dimensional (3D) motion capture systems (Beak et al., 2013; S. J. Brown et al., 2011; Horan et al., 2011; Horan et al., 2010; Horan & Kavanagh, 2012; Myers et al., 2008) and Doppler radar equipment (*e.g.* Flightscope launch monitor and Trackman) is also used to asses drive performance (Masuda, Yataka, Chujo, Kondo, & Iijima, 1994). While 3D motion capture remains the current gold standard for measuring swing biomechanics and parameters contributing to drive performance (Beak et al., 2013; S. J. Brown et al., 2011; Horan et al., 2011; Horan et al., 2010; Horan & Kavanagh, 2012; Kadowaki et al., 2006; Myers et al., 2008), its use is not practical in a field-based setting (*i.e.* driving range and golf course) to measure rotational velocity.

The Doppler radar systems (*e.g.* Flightscope launch monitor and Trackman) can measure swing parameters such as ball speed, launch angle, CHS and club angle in a field-based environment. However, these devices cannot quantify the angular velocity of body segments. Therefore, IMU have been implemented to estimate upper-limb (Zhang & Wu, 2011), trunk (Koyama, Nishiyama, & Watanabe, 2013) and swing motion (Ghasemzadeh et al., 2009; Hsu et al., 2016; Nam et al., 2014; Ueda et al., 2013). The IMU can track the golf club trajectory and motion during the swing by placing the sensors on various body segments to measure rotational velocity using a single three-axis accelerometer (Song, Park, & Kim, 2010), or a combination of accelerometers and gyroscopes (King, Yoon, Perkins, & Najafi, 2008; Negoro, Ueda, Watanabe, Kobayashi, & Kurihara, 2011). Previous investigators have also attached IMU on the golf shaft (Ahmadi et al., 2014; Cao et al., 2013; Hsu et al., 2016; Nam et al., 2014; Seaman & McPhee, 2012), lead wrist (Ghasemzadeh et al., 2009) and/or on the end of the club (grip end) (Ueda et al., 2013) to measure multi-segmental rotational velocities during a single swing. Additionally, IMU have been used in combination with 3D motion capture as a reference system to determine the validity of the sensors to track the golf swing movement when placed on the golf shaft (Seaman & McPhee, 2012) and grip end (Ueda et al., 2013). According to Seaman and McPhee (2012), the micro-electromechanical-system IMU placed on the golf shaft creates too much noise in the gyroscope channels. Additionally, the micro-electromechanical-system IMU sensor does not have the dynamic range to successfully measure the golf swing as during the downswing the magnitude of rotation peaks around 2,500 deg/s and 35G, respectively for male golfers. Thus, it was determined that the rotational velocity of different phases of the golf swing could not be accurately assessed (Seaman & McPhee, 2012). In contrast, when the IMU was placed on the end of the golf grip, a high correlation was shown in angular velocity (*i.e.* R values of 0.97, 0.99 and 0.98 for x-, y- and z-axis angular velocities, respectively) between the inertial sensor and 3D motion capture system (Ueda et al., 2013). However, it is possible that when an IMU is placed on the golf shaft and/or golf club head this will increase the golf club weighting which may change the golf shaft properties (*i.e.* golf flex and kick-point of the golf shaft). Such a change may potentially disrupt swing mechanics and/or increase swing variability which will lead to negative changes in CHS for drive performance (Myers et al., 2008). Additionally, there are commercially available golf products on the market (*e.g.* K-Vest, Skypro and Zepp) which utilise inertial sensors placed on the golf shaft, hand, thorax and pelvis segments to measure the golf swing. However, to date there are no published studies on the reliability of IMU placement on different body segments (*e.g.* wrist, thorax and pelvis) and the golf club head to determine rotational velocity of the golf drive.

According to golf swing mechanics and the kinetic link principle, the movement of the golf swing should commence with larger, proximal segments (*i.e.* thorax and pelvis) and then proceed in a sequential manner to distal segments (*i.e.* shoulders, forearms, hands and club shaft) to generate rotational velocity and maximise CHS (Okuda et al., 2010). Additionally, during the kinematic sequencing of the swing, the last body segment to transfer the rotational velocity to the golf club is the release of the wrist at ball impact (Hume et al., 2005). Therefore, changes in upper-body rotational velocity can cause changes in the rotational velocity of the lead wrist which may influence CHS. Therefore, the purpose of this investigation was to determine the reliability of the IMU placed on the lead wrist to measure changes in rotational velocity of the golf swing. It was hypothesised that; 1) the IMU would produce a reliable measure of rotational velocity of the golf swing and, 2) a high rotational velocity measured using the IMU is associated with a high CHS measured using the Flightscope launch monitor.

3.3 Methods

3.3.1 Experimental approach to the problem. Ten participants were recruited for two separate testing occasions separated by seven days. The two data collection occasions were used to establish test-retest reliability of the protocol as shown by an intraclass correlation co-efficient (ICC), coefficient of variation (CV) and the change in mean (CM). Additionally, anthropometric data (*i.e.* height, weight, age, HCP) was collected before each testing session.

3.3.2 Participants. Ten right-handed female participants (age 40.5 ± 18.84 yr [range = 18-61 yr], body-mass 65.6 ± 12.76 kg, body-height 164.3 ± 5.8 cm and HCP 6.2 ± 2.6), with and without resistance training experience were recruited for this investigation from golf clubs and golf courses in Auckland region, New Zealand. All participants were required to fit the inclusion criteria of: 1) female aged ≥ 16 yr, 2) currently have a HCP of ≤ 10, 3) have no current acute or chronic injuries and/or medical conditions that may inhibit participation to the full extent of the testing sessions, and 4) are not using any performance enhancing or banned substances (World Anti-Doping Agency, 2017). All participants signed an informed consent form prior to participation of testing session. To ensure the safety of the participants, all testing conditions were examined and approved by the Auckland University of Technology Ethics Committee (Ethics number 17/41).

3.3.3 Testing protocols. Prior to the data collection period, all participants were required to attend a familiarisation session of the standardised warm up and testing protocols. Two testing sessions were performed at the same time of day separated by minimum of six days and maximum of seven days' duration at the Takapuna driving range (North Shore, Auckland, NZ). All participants' anthropometric data (*i.e.* age, body-mass, body-height and HCP) were collected at the beginning of each testing session. Prior to the data collection, all participants performed a standardised warm-up consisting of three minutes of dynamic arm swings, leg swings, leg side turns, trunk rotations which mimic the golf swing and golf swings in the air with an iron golf club. Following the dynamic warm up, the participants performed a standardised golf practice which consisted of five golf shots each with a nine-iron, five-iron and driver. All participants utilised their own golf clubs as changes in golf equipment may disrupt swing mechanics (Myers et al., 2008). After the completion of the standardised golf warm up and practice protocol, the participants were required to complete 10 maximal attempts with their driver with a two-minute rest between each maximal attempt. An experienced golfer observed each golf swing to assess technical proficiency. If a participant acutely demonstrated poor technique mechanics, further trials were given until ten reliable trials were completed. The average of the ten maximal effort trials were reported for each participant and used for further data analysis (Fletcher & Hartwell, 2004; Thompson et al., 2007).

3.4 Equipment

The IMU (Sabel Sense, SABEL Labs, Brisbane, QLD, AUS) consists of an accelerometer (+16g), gyroscope (+2400 deg/s) and magnetometer all sampled synchronously at 250 Hz. The Flightscope launch monitor (Xi, Flightscope [Pty] Ltd., Orlando, FL, USA) is a 3D Doppler ball tracking radar with a golf application that can measure club variables such as CHS. The Flightscope launch monitor is a reliable (ICC = 0.87), accurate and valid system to track CHS measured at ball impact for male golfers (Read, Miller, & Turner, 2013) to determine golf drive performance (Chu et al., 2010).

The IMU was attached to participant's lead wrist in line with the radius-styloid and ulna-styloid processes (Figure 2). The Flightscope launch monitor was placed 3 m behind the participant, in line with the golf ball (Figure 3). All participants aimed at a target marker at the driving range (*i.e.* 300 metres outdoor range) that was directly in line with the participant's golf ball and the Flightscope launch monitor. The Flightscope launch monitor was aligned via a camera within the system and the data were projected through a digital application.

Figure 2. Location of the IMU on the lead wrist of right-handed skilled female golfers.

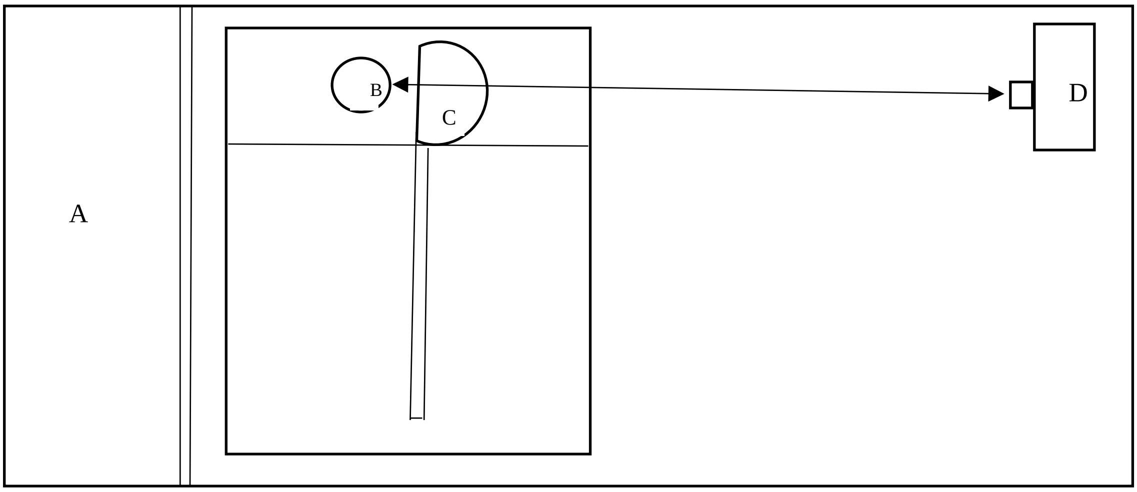


Figure 3. The setup of the golf drive performance testing.

A = driving range. B = golf ball. C = golf club (i.e. driver). D = Flightscope launch monitor. The Flightscope launch monitor was placed 3 meters away from the golf ball and positioned in line with the middle of the golf ball.

3.5 Data Analysis

Accelerometer and gyroscope data collected by the IMU during the golf drive was further analysed manually using MATLAB software (R2017a, The MathWork, Inc., Natick, MA, USA) to determine the peak rotational velocity of the lead wrist. The peak rotational velocity of the IMU on the lead wrist was determined manually by locating the accelerometer time point one frame before ball impact of the golf drive (Figure 4). The peak rotational velocity of the lead wrist was not determined at ball impact as rotational velocity at impact may be influenced by ball contact, inconsistency of ball striking (*i.e.* golf club face angle) and golf club properties (*i.e.* golf club flex, stiffness of golf club, golf shaft bend point, golf shaft kickpoint) which may influence the amount of rotational velocity generated. Ball impact was determined by the sharp changes/spikes from x- or y- or z-axis in accelerometer channel (Figure 4).

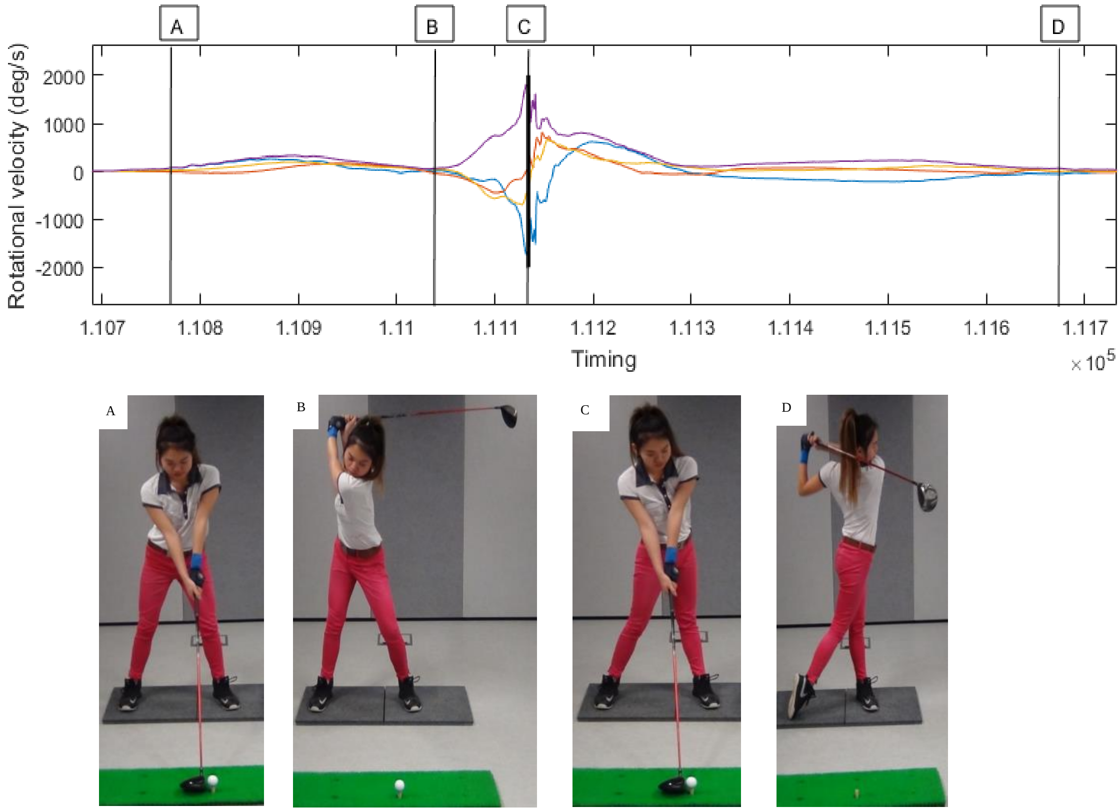


Figure 4. The rotational velocity of the different phases of the golf drive

A. Address. B. Top of backswing. C. Downswing to impact. D. Finish

3.6 Statistical Analysis

Mean and standard deviation of ten maximal trials across each testing occasion were used to establish test-retest reliability. The mean of ten maximal trials within each data collection occasion was used to establish test-retest reliability. Reliability was established via three separate statistical methods; 1) the change in mean (CM), a percentage fluctuation in mean to establish if average performance increased or decreased across the data collection occasions, 2) the co-efficient of variation (CV), to determine typical error as a percentage of each participants mean, and 3) intraclass correlation (ICC), to indicate the consistency of an athletes score in relation to the group. The current investigation set reliability thresholds at a CV ≤ 10% (Atkinson & Nevil, 1998) and ICC ≥ 0.70 (Meylan, Cronin, Oliver, Hughes, & McMaster, 2012). Ninety percent confidence intervals (90% CI) were reported for all between trial statistics. All reliability data were analysed using Hopkins (2000) reliability excel spreadsheets.

3.7 Results

The CHS measured using the Flightscope launch montior was observed to be reliable measure (CM = -0.18%, CV < 10%, ICC = 0.98). However, rotational velocity measured using the IMU demonstrated a high variability between trials (CM = -17.59%, CV > 10%, ICC = 0.92) (Table 6). According to figures 5 and 6, CHS showed greater test-retest reliability and less test-retest variability in comparison to the rotational velocity of the lead wrist as a means to measure golf drive performance.

Table 6

Reliability of the Inertial Measurement Unit and Flightscope Launch Monitor to measure Golf Drive Performance

	Mean ± SD		Coefficient of variation (%)		Change in the mean (%) (CI)	Intraclass correlation (ICC)
Variables	Day 1	Day 2	Day 1	Day 2	Days 1 – 2	Days 1 -2
CHS (m/s)	36.76 ± 2.39	36.57 ± 2.50	6.50	6.83	-0.18 (-0.48 - 0.11)	0.98 (0.95 - 1.00)
RV (deg/s)	1432.04 ± 165.92	1414.45 ± 180.94	11.59	12.79	-17.59 (-62.57 - 27.39)	0.92 (0.78 - 0.98)

Key: CHS = club head speed; RV = rotational velocity.

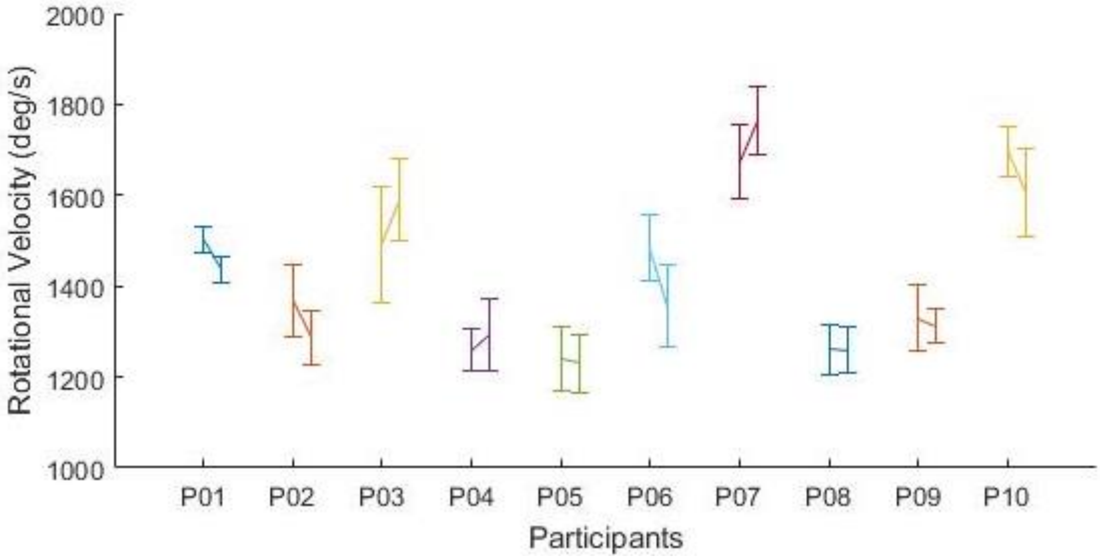


Figure 5. Test-retest reliability of participants' rotational velocity of the golf drive using IMU.

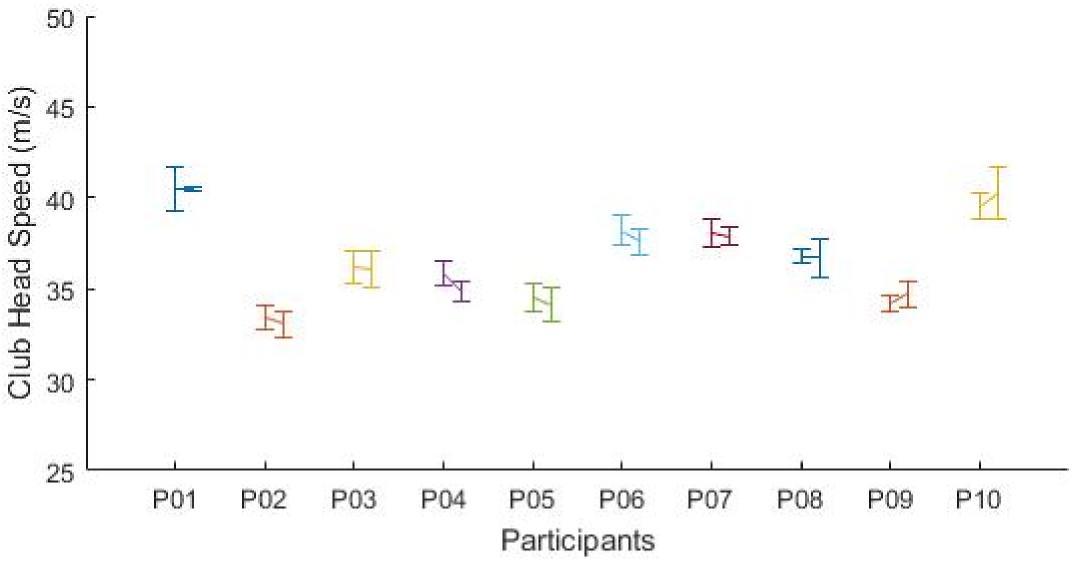


Figure 6. Test-retest reliability of participants' CHS of the golf drive using flightscope launch monitor.

3.8 Discussion

The purpose of this investigation was to quantify the reliability of the IMU placed on the lead wrist to measure rotational velocity of the golf drive and CHS on skilled female golfers. In addition, this investigation was the first to report the reliability of a golf drive rotational velocity assessment as previous researchers have examined rotational velocity using equipment such as cable machine and medicine balls (Atkinson & Nevil, 1998). As such, it was determined that the IMU placed on the lead wrist resulted in a non-acceptable, high degree of variability with regards to rotational velocity of the golf drive.

Previous investigators examining rotational power have assessed neuromuscular characteristics by utilising equipment such as cable machine and medicine balls. For example, side medicine ball throws, seated cable rotations, dynamometry and golf-specific cable rotations are all assessments which have reported ICC reliabilities of 0.89-0.97 (Andre et al., 2012; Bradley et al., 2009; Ikeda, Kijima, Kawabata, Fuchimoto, & Ito, 2007; Ikeda, Miyatsuji, Kawabata, Fuchimoto, & Ito, 2009; Sell et al., 2007). However, these reliability studies assessing rotational power did not include full reliability statistics (Andre et al., 2012; Bradley et al., 2009; Ikeda et al., 2007; Ikeda et al., 2009; Sell et al., 2007).

Rotational ability is important in the golf swing as rotational velocities have differentiated between high and low CHS for male and female golfers (S. J. Brown et al., 2011; Chu et al., 2010; Okuda et al., 2010). Additionally, there are significant correlations between rotational speed (r = 0.67) (Read, Lloyd, et al., 2013), power (r = 0.54) (Bradley et al., 2009), strength movements (r = 0.71) (Keogh et al., 2009) and CHS. Therefore, the ability for golfers to produce high levels of power, speed and rotational strength during the golf drive is required for high CHS and drive distance (Nesbit, 2005). In the downswing, a rapid production of force against the load of the golf driver (i.e. a typical golf driver <800 g) is required to produce a high rotational velocity. This in turn creates high CHS through to ball impact and follow-through and contributes to drive distance (Nesbit, 2005). Therefore, changes in rotational velocity may cause changes in CHS.

The CHS variable obtained from the Flightscope launch monitor showed greater reliability (CV and ICC) compared to rotational velocity obtained from the IMU (Table 6). There are many factors that can potentially influence CHS: 1) swing mechanics, 2) swing variability, 3) golf club properties (i.e. shaft and golf club head weighting, golf flex, flex bend point and flex kick point) and, 4) the neuromuscular characteristics (*i.e.* upper- and lower-body strength and rotational power) of the golfer. Skilled female golfers often have refined swing mechanics, lower swing variability and optimised golf shaft properties and design help to generate CHS (Chu et al., 2010; Sell et al., 2007; Zheng et al., 2008). Therefore, a high reliability in CHS may be due to a combination of these factors. In contrast, the rotational velocity of the IMU when placed on the lead wrist demonstrated a poor level of reliability which may possibly be due to the heterogenous skilled female golf sample (*i.e.* age and neuromuscular characteristics). Although, all skilled female golfers recruited in this study had a HCP of ≤ 10, the differences in neuromuscular characteristics (*i.e*. golfers with and without resistance training experience) and age (range = 18 to 61 yr) may have contributed to the large variation in mean and standard deviation of rotational velocity for skilled female golfers. Age-related declines in muscular strength and power are known to occur starting from the fourth decade in life (Macaluso & De Vito, 2004; Skrzek, Ignasiak, Kozieł, Sławińska, & Rożek, 2012). As the age range [18 to 61 yr] of participants in this research study substantially crossed this gap, there may have been important differences in neuromuscular characteristics which led to our current results.

Thus, further research is required on a larger, homogenous sample size of skilled female and/or male golfers (HCP ≤ 10) with similar age group (*i.e.* younger participants < 30) and resistance training experience (*i.e.* at least 1 year) to determine the reliability of the IMU placed on the wrist to measure rotational velocity of the golf drive.

3.9 Limitations

Several limitations specific to the measure of rotational velocity of the golf drive swing motion exist within this study and should be acknowledged in the interpretation of our results. The IMU was only placed on the lead wrist to determine lead wrist rotational velocity. However, it does not provide further information on changes in rotational velocity of the thorax segment and/or pelvis. To determine the golf swing kinematic sequence of the different body segments (*e.g.* thorax and pelvis) further research is required on skilled female golfers. Additionally, environmental factors (*i.e.* wind, rain, grass conditions) and differences in golf balls can cause changes to total drive distance measured using Flightscope launch monitor (Fletcher & Hartwell, 2004). As a result from such environmental factors, only CHS was used in this study as a measure of golf drive performance. A correlation between CHS and rotational velocity was not determined due to the small sample size of female golfers and the restricted HCP criteria (*i.e.* HCP $\leq$ 10), therefore further research is required. Lastly, as the current reliability study only included female participants, the findings cannot be generalised to male golfers.

3.10 Conclusion

The current investigation has demonstrated that an IMU placed on the lead wrist of skilled female golfers does not provide a reliable measure of rotational velocity during the golf drive. Therefore, the current protocol should not be utilised to quantify pre-to post-change in rotational velocity of the golf drive. Further research is required on a larger, homogenous sample size to determine the reliability of the IMU to measure rotational velocity during the golf drive when placed on different sites on the body (*i.e*. wrist, thorax and pelvis).

Chapter Four:

The effects of a six-week ballistic and plyometric training programme on female golfers' drive performance and neuromuscular characteristics

4.1 Preface

As found in the systematic review of the literature, majority of the golf resistance training programmes have been prescribed for male golfers utilising strength and power type training (*i.e.* ballistic and plyometric exercises) methods and most of these interventions resulted in improvements in CHS. However, the effects of a ballistic and plyometric resistance training on female golfers remain unknown. Therefore, the overarching question for this chapter is "what are the effects of a six-week ballistic and plyometric training programme on female golfers' drive performance and neuromuscular characteristics?" In order to address this research question, a six-week ballistic and plyometric training protocol was undertaken involving two highly-skilled female golfers (HCP < 5). Key variables of interest were their drive performance (*i.e.* CHS) and changes in their neuromuscular characteristics (*i.e.* upper- and lower-body peak power).

4.2 Introduction

Maximal drive distance requires golfers to apply high forces and velocity to the golf club in a short time frame through refined, efficient swing mechanics (Nesbit, 2005). Therefore, maximising swing biomechanical factors will lead to an increase in CHS (Chu et al., 2010; Zheng et al., 2008). However, when golfers' consistently demonstrate refined swing mechanics (*i.e.* angular displacement and velocity of pelvis and thorax, and X-factor stretch) with low endpoint movement variability, additional methods such as resistance training are required to further improve CHS (S. J. Brown et al., 2011; Chu et al., 2010; Vena, Budney, Forest, & Carey, 2011). Previous investigators have reported increases in CHS (1.20 to 10.00 m/s [2.68 to 22.36 mph]) post training programmes (*i.e.* hypertrophy, flexibility, rehabilitative, functional movement and strength) for male and/or female golfers (Alvarez et al., 2012; Chen et al., 2010; Doan et al., 2006; Kim, 2010; Lephart et al., 2007; Thompson et al., 2007; Weston et al., 2013). Furthermore, recent studies have reported improvements in CHS following golf-specific ballistic exercises (*e.g.* side rotational throws and weighted golf club swings) and plyometric exercises (*e.g.* CMJ, SJ, box jumps and hurdle jumps) for male golfers (Alvarez et al., 2012; Bliss et al., 2015; Ghigiarelli et al., 2015). However, the effects of ballistic and plyometric training for female golfers remains unknown. Sex-related differences (*i.e*. neuromuscular characteristics, anatomical and physiological) may influence the ability to adapt to different types of golf resistance training protocols. As such, the results of golf resistance training programmes for male golfers cannot be generalised to female golfers. Therefore, further investigation is required to determine the effects of ballistic and plyometric training on female golfers' drive performance and neuromuscular characteristics.

According to Hume et al. (2005) the average downswing phase of the golf drive is approximately 230 ms, which is shorter than the requirement to generate maximal force (> 300 ms). To further generate CHS it is important to train the velocity component and/or increase the rate of force production to apply maximal force in the short/available time within the golf swing. Ballistic training can increase explosive power output (*i.e.* peak power) and rate of force development. Ballistic training is performed in an explosive manner to emphasise the fast loading of eccentric phase followed immediately by a concentric muscle action to utilise the SSC to increase elastic energy production (Bliss et al., 2015; Fletcher & Hartwell, 2004). According to the current golf literature, golf-specific ballistic exercises and plyometric exercises are often progressively incorporated into resistance training programmes for male golf participants with no previous resistance training experience (Alvarez et al., 2012; Doan et al., 2006; Lephart et al., 2007; Thompson et al., 2007). Previous investigations which have prescribed combined strength, ballistic and plyometric training programme for skilled male golfers (*i.e*. HCP = 0 - 9) have shown significant improvements in CHS (*i.e.* 0.76 - 1.5 m/s [1.7 -3.3 mph]) (Doan et al., 2006; Fletcher & Hartwell, 2004). Additionally, when ballistic exercises (*e.g.* side rotational throws and chest throws) and plyometric exercises (*e.g.* CMJ, SJ, box jumps and hurdle jumps) were solely prescribed to skilled male golfers (HCP = 4.7 ± 3.0, without previous ballistic training), researchers noted improvements in neuromuscular characteristics and CHS (*i.e.* 0.8 m/s [1.78 mph]) (Bliss et al., 2015). Due to the sex-related differences in the neuromuscular characteristics, anthropometry and swing mechanics of golfers (S. J. Brown et al., 2011; Horan et al., 2011; Horan et al., 2010), it is uncertain whether the same positive outcomes would occur following ballistic and plyometric training for female golfers. Thus, the primary purpose of this study was to determine the effects of a six-week ballistic and plyometric training programme on female golfers' drive performance and neuromuscular characteristics. It was hypothesised that improving upper- and lower-body power via ballistic and plyometric training would result in substantial improvement in golf drive performance (CHS).

4.3 Methods

4.3.1 Experimental approach to the problem. Highly-skilled female golfers (HCP < 5) were recruited for this investigation due to their refined swing mechanics as to minimise the potential effects of changes in swing technique. All participants were required to have a least one year of resistance training experience to ensure they had adequate neuromuscular control and dynamic strength in the core musculature before performing ballistic and plyometric exercises (Lephart et al., 2007; Thompson et al., 2007). According to Horton et al. (2001) a lack of resistance training experience could potentially cause an injury to lower back due to poor recruitment of abdominal musculature when performing ballistic and plyometric exercises. Due to the limited population of highly-skilled female golfers with resistance training experience within the Auckland region of New Zealand, a single-subject design was used to assess the effects of a six-week ballistic and plyometric training programme on female golfers' drive performance and neuromuscular characteristics.

Two highly-skilled female golfers (HCP < 5) undertook a six-week pre-intervention (control) followed by a six-week training intervention (experimental) and then a four-week post-intervention (non-training). The single-subject design caters for a smaller sample size whilst still providing data for comparisons between an experimental and control period (Lynch, 2010). The entire study period took a total of 16 weeks and comprised of: (1) an initial testing week (week 0); (2) a six-week pre-intervention period (weeks 1 to 6); (3) a six-week intervention period (weeks 7 to 12); and (4) a four-week post-intervention period (week 12 to 16). Six performance testing sessions were conducted in total during weeks 0, 3, 6, 9, 12 and 16. During the six-week control period, the participants continued with their regular golf training in the absence of ballistic and plyometric training programme. During the experimental period, the participants continued with their regular golf training and golf competitions requirements with the inclusion of a prescribed ballistic and plyometric training programme. Finally, during the non-training period, the participants continue with their regular golf training and golf competitions requirement without performing ballistic and plyometric training to determine the effects on drive performance and neuromuscular characteristics. As none of the participants participating in this study were practicing any structured ballistic and plyometric training of any kind before the study, the study design commenced with an initial control-block period for both participants. During the control period, multiple baseline values were captured to determine the participants' individual variability (single-subject standard deviation) in golf drive performance and neuromuscular characteristics measures. The individual change in the experimental period was compared with the control period to determine whether the intervention elicited a greater effect than the individual variability (Hopkins, 2008). The results were analysed visually for trend, variability and change in level. Additionally, the results were statistically analysed via the ± 2 standard deviation band method (± 2 SD) (post mean above/below pre-mean ± 2SD) to identify substantial pre-to post-change (Nourbakhsh & Ottenbacher, 1994).

4.3.2 Participants. Two highly-skilled female golfers (HCP < 5) volunteered to participate in this study. The mean age, body-mass, body-height and HCP of the participants were 20 ± 1.4 yr, 58.4 ± 10.9 kg, 162.5 ± 3.6 cm and 2.0 ± 1.9 HCP, respectively. Both participants had not previously performed ballistic and plyometric exercises or had no current acute or chronic musculoskeletal injuries and/or medical conditions that may inhibit their participation of the full extent of the training programme. The participants did not use any performance enhancing or banned substances (World Anti-Doping Agency, 2017) and the risks of the research study were explained prior to signing the informed consent form. All procedures and protocols were approved by the Auckland University of Technology Human Subject Ethics Committee (Ethics number 17/41).

4.3.3 Equipment. Participants performed neuromuscular characteristics testing in the following sequential order for all testing sessions: 1) upper-body testing (static and dynamic chest throws, and static and dynamic side rotational throws left and right side), 2) lower-body testing (CMJ and SJ), and 3) golf drive performance testing (CHS via Flightscope).

1) Upper-body power testing

To measure upper-body rotational power participants threw a medicine slam ball (3 kg) and the distance thrown was quantified using a measuring tape and video analysis. A 6 m measuring tape was placed on the floor horizontally and a one-metre tape was placed and marked incrementally every 10 cm vertically to allow for estimation of throw distance using video analysis (Figure 7). A high-speed camera (Casio Ex, 200 frames per second) was placed 1 m in line with participant's estimated throwing distance and Kinovea digitising software (v 0.8.26, Kinovea NPO, FRA) was used to measure throw distance. Additionally, the camera was positioned to encompass the estimated throwing zone based on participant's practice throw trials for each throw and testing session. A previous investigation has demonstrated that Kinovea is a highly reliable (r = 0.9997) method to quantify athletic movements (Balsalobre-Fernández, Tejero-González, del Campo-Vecino, & Bavaresco, 2014). Following two practice trials to determine participants target range of distance. The camera was then subsequently moved to capture the required field of view (*i.e.* 1 m) zone encompassing the target range to video the ball impact and calculate the total distance thrown.

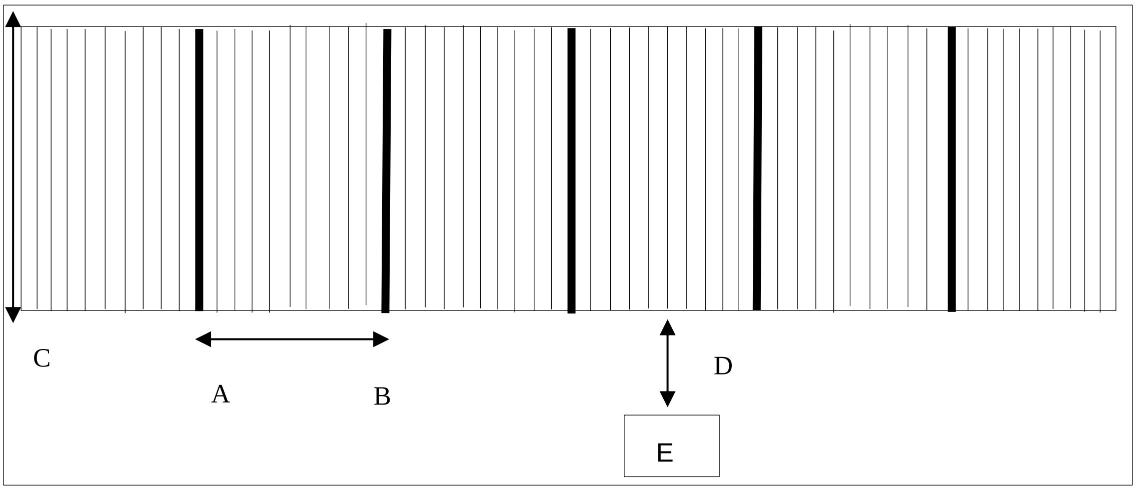


Figure 7. The setup of the upper-body throws testing.

A to B = 1 m tape was placed horizontally and marked for a total of 6 m. C = 1 m tape was marked incrementally every 10 cm vertically. D = 1 m between the tape and the camera. E = camera was positioned to encompass 1 m of the estimated throwing zone based on participant's practice throw trials.

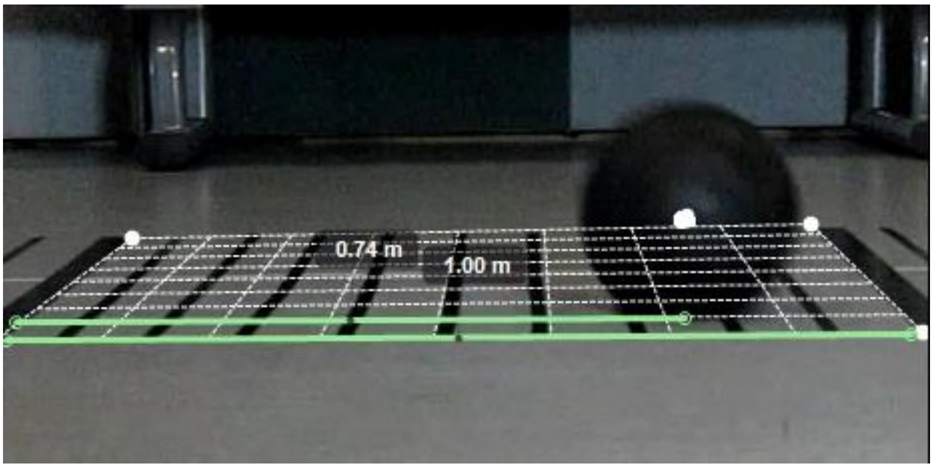


Figure 8. Throw video analysis using Kinovea digitising software.

2) Lower-body power testing

The CMJ and SJ were performed on an AMTI force platform (AccuPower, Advanced Mechanical Technology, Inc., Watertown, MA, USA) which has been reported as the gold standard for measuring maximum peak power (Nigg & Herzog, 2007). Data were recorded at 1000 Hz using a custom-designed LabVIEW programme (v14.0, National Instruments Corp., Austin, TX, USA).

3) Golf drive performance testing

The Flightscope launch monitor (Xi, Flightscope [Pty] Ltd, Orlando, FL, USA) is a 3D Doppler tracking radar with a golf application that can measure CHS. Previous investigators have determined Flightscope to be a reliable (ICC = 0.87), accurate and valid system to track CHS measured at ball impact (Read, Miller, et al., 2013). The Flightscope launch monitor was positioned 3 m posterior to the golf ball in line with the intended target line. Both participants performed all trials off artificial astro turf and a rubber golf tee. Participants stood on mats which were leveled to the same height as the artificial astro turf. A golf net was setup in a laboratory environment to avoid environmental factors (*i.e.* wind and rain) and both participants used the same brand of golf ball (Pro V1, Titleist, Fairhaven, MA, USA) throughout all of the testing sessions as these may cause changes to drive performance (*i.e.* CHS) (Bliss et al., 2015; Fletcher & Hartwell; 2004). Additionally, participants used their own driver to avoid unfamiliarity with changing golf equipment which can cause changes to CHS due to structural properties (*i.e.* design, stiffness, weight and length) of the golf club (Keogh et al., 2009).

4.3.4 Testing procedures. On all testing occasions, participants were instructed to follow their daily nutritional routine and to arrive at the testing facility in a rested state following a 24 h break from exercise. The neuromuscular characteristics performance session consisted of two sections (*i.e.* upper- and lower-body power measures) which were performed consecutively. A 15 min rest was given after neuromuscular characteristics performance collection followed by golf drive performance testing. Participants were given a full introduction to all assessments before the proceeding of the testing session. Anthropometric, neuromuscular and golf drive performance testing sessions were established at the same time of the day (i.e. approximately between 12 to 3 pm) for all testing sessions.

***4.3.4.1 Anthropometric data*.** Anthropometric data (body-mass and -height) was taken at the start of every testing session. Body-mass was determined to the nearest 0.01 kg using a calibrated electronic scale (Seca 876, Seca Medical Measuring Systems and Scales, Hamburg, DEU). Participant’s body-height was measured to the nearest 0.1 cm using a harpenden wall mounted stadiometer (Harpenden Wall Mounted Stadiometer, Holtain Model 602VR, PB, UK) fixed to a wall.

4.3.4.2 Pre-testing warmup. Both participants were required to perform a standardised warm up consisting of 5 min of dynamic stretching (medial-lateral, anterior-posterior leg swings, arm swings, trunk rotations, single leg kneeling trunk rotations, body weight squats, walking knee to chest, heel raises, high knees and butt kickers) before the neuromuscular characteristic testing. Additionally, before commencing the golf drive performance testing, participants completed a standardised warm up consisting of five shots using a nine iron, five iron and a driver at submaximal exertions.

4.3.4.3 The upper-body measures of power. A seated chest throw (Figure 9) was used to measure upper-body power output as this movement has been shown as a highly reliable measure (ICC = 0.94) and is significantly correlated with CHS (p = 0.01, r = 0.67) (Read, Lloyd, et al., 2013). Participants were seated on an incline bench (45°) with their feet flat on the floor as per the protocols outlined by Hegedus et al. (2016). The seated chest throw was performed statically (i.e. with an initial pause to minimise/eliminate the utilisation of SSC) and dynamically (to promote the utilisation of the SSC). To perform the static chest throw, participants held a 3 kg medicine ball against their chest and were instructed to throw the ball with both hands as far as possible. To perform the dynamic chest throw, participants initially held a 3 kg medicine ball at arms' length and were instructed to rapidly bring the ball to their chest prior to release without a pause. Participants had three practice throws followed by three recorded maximal effort trials. The average of the three throws were reported for both static and dynamic throws. A 1 min rest period was given after each throw (Hegedus et al., 2016). The throws were marked at first contact with the ground and measured in centimetres and quantified by measuring tape and video analysis.

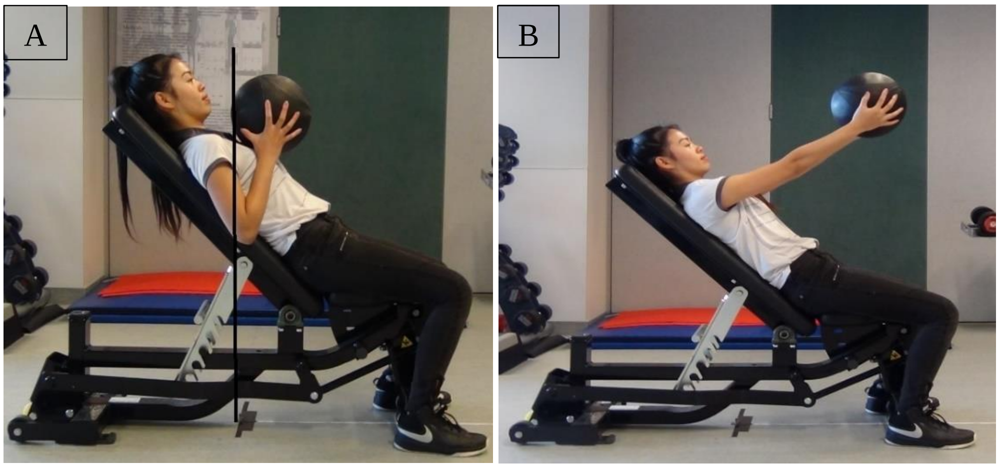


Figure 9. The seated static and/or dynamic chest throw.
A = Start position for static throw. B = Start position for dynamic throw.

A side rotational throw was used to measure upper-body rotational power output (Figure 9). Side rotational throws (right and left side) are reliable (ICC = 0.90) measures of upper-body rotational power and are significantly correlated with CHS (p = 0.05, r = 0.63) (Bradley et al., 2009; Read, Lloyd, et al., 2013). The side rotational throw followed the protocols outlined in Hegedus et al. (2016) and Bradley et al. (2009). Participants were instructed to take a golf stance while holding a 3 kg medicine ball and to mimic the golf backswing (*i.e*. to rotate the thorax until the ball has reached chest height), followed by a downswing and follow-through which the ball was released at chest height as far as possible. The participants were instructed to keep their feet planted on the floor during the backswing and their trail heel (*i.e*. right foot for a right-handed golfer) was allowed to come off the floor during the downswing to follow-through to mimic the golf swing. The side rotational throws were performed statically (*i.e*. with an initial pause for 3 s at the top of the backswing position to minimise/eliminate the utilisation of the SSC) and dynamically (*i.e*. without a pause in the backswing to promote the utilisation of the SSC). The corresponding throw distances were quantified by measuring tape and video analysis (Bradley et al., 2009; Justin, Nesser, Demchak, & McMannus, 2012; Read, Lloyd, et al., 2013). Participants had three warm-up throws followed by three recorded trials for all static and dynamic throws on their left and right side. A 1 min rest was given after each throw. The mean of the three maximal effort trials was reported.

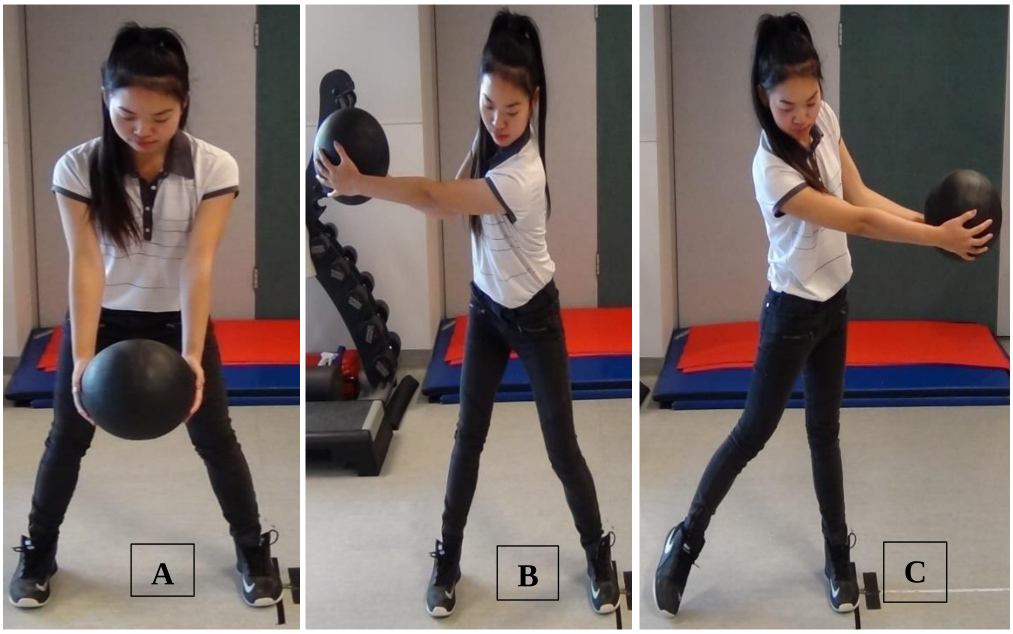


Figure 10. The static and/or dynamic side rotational throw.

A = Start. B = Pause position for static throw. C = Release position.

***4.3.4.4 The lower-body measures of power*.** The CMJ and SJ were used to measure lower-body peak power output as moderate correlations between these measures and CHS (r = 0.61 and 0.53, respectively) have been reported (Read, Lloyd, et al., 2013). Previous researchers have also shown high reliability of the CMJ (ICC = 0.97, CV = 2.8%) and SJ (ICC = 0.91, CV = 3.2%) to determine maximum relative peak power (Nigg & Herzog, 2007). Lower-body measures of power were performed in accordance with the protocol outlined by Leary et al. (2012). Participants performed three practice trials followed by three maximal attempt efforts for both the CMJ and SJ on an AMTI force platform. A 1 min rest was given between each maximum jump trial. To perform the CMJ, participants were instructed to place their hands on their hips, descend until their thighs were approximately parallel to the ground at a 90 degrees angle and jump as fast and high as possible with a minimal timeframe between the eccentric and concentric phase (*i.e.* to promote utilisation of SSC). To perform the SJ, the participants were instructed to hold a squat position (thighs parallel to the ground at a 90-degrees angle) for 3 s to minimise utilisation of the SSC, followed by a jump as fast and as high as possible. The three maximal effort trials were used for data analysis to determine the maximum relative peak power.

4.3.4.5 The golf drive performance measures. The golf drive performance followed the protocol outlined in Chapter Three. Participants completed ten maximal attempts with their driver and the corresponding CHS were measured using Flightscope. Participants were given a 1 min rest interval between each maximal attempt. All participants aimed at a target marker on the golf net that was directly in line with the participant's golf ball and the Flightscope. The Flightscope was aligned via a camera within the Flightscope that projects the surroundings through the software. An experienced golfer observed each swing to assess technical proficiency. If a participant acutely demonstrated poor technique mechanics, a further trial was given until ten reliable trials were completed as reported by previous studies (Fletcher & Hartwell, 2004; Thompson et al., 2007). The average of the ten maximal effort trials were reported for each participant and used for analysis.

4.3.4.6 Training programme protocol*.* The golf training intervention was implemented through the 2017 New Zealand competitive off season (July-October). Prior to undertaking the programme, both participants were involved in a familiarisation training session which consist of the ballistic (upper-body throws and weighted golf sticks) and plyometric (lower-body jumps) technique session from an experienced strength and conditioning coach. Participants were instructed to refrain from all other forms of resistance training and cardiovascular training that may influence the results of the training intervention. Additionally, participants were informed about hydration and nutritional requirements but no specific dietary plans were undertaken. All resistance training sessions were supervised by the lead researcher with specific attention to correct exercise technique. Technical feedback was given by the method of video and knowledge of exercises and golf swing mechanics. Additionally, motivation and encouragement was given to both participants to move the load and perform the exercise as fast as possible throughout all training session and testing session.

Upper-body ballistic exercises were initially performed with 3 kg medicine balls and progressed to 4 kg after week 10. The weighted golf swings were performed using Superspeed golf sticks which are golf-specific training tools designed to increase CHS for the golf drive (SuperspeedGolf, 2018). Light (255 g) Superspeed golf sticks was initially used and the participants progressed to medium weighted golf sticks (285 g) on week 9 and progressed to heavy weighted golf sticks (335 g) on week 11. The CMJ and SJ intensity progressively increased by adding dumbbell loads of 5-10% body-mass. This was implemented by week 7 (body-mass), week 8 and 9 (5% body-mass), week 10 and 11 (10% body-mass) and week 12 (body-mass). The participant's initial box jump height and hurdle height was set at double their CMJ height, and progressively increased by 5% of CMJ height every week, with a deloading week in week 10 and a tapering week in week 12. The number of hurdles progressively increased according to the sets and reps (Table 7) and the hurdles were placed 50 cm apart to ensure participants jump with high velocity and short ground contact time.

4.3.4.7 Program structure. Both participants performed the training intervention three times per week during the six-week experimental period and the exercise order was kept constant throughout the training programme (Table 7). During the six-week experimental period, the ballistic and plyometric exercises progressively increased throughout the training intervention in volume (sets and reps) in a safe manner to prevent injury and ensure adequate training stimulus. The relative training intensity remained the same (~90-100% of perceived maximal effort) and 2 min rest periods were given between sets. A "deloading week" (*i.e.* reduction in training volume) was implemented on the fourth week to allow for recovery. Training days 1-3 were separated by one day of rest.

Table 7

Sixteen-week Period comprised of a Six-week Control-block, a Six-week Experimental-block and a Four-week Non-training-block.

S	Exercise		Control						Intervention						
		W0	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W16
1	WGS (R), WGS (L), CMJ, SSRT (R), BJ, SSRT (L), JOH								3x4	3x5	3x6	3x4	4x5	3x6	
2	WGS (L), WGS (R), SJ, DSRT (R), BJ, DSRT (L), JOH, SCT								3x5	3x6	4x5	3x5	4x6	4x5	
	Performance Test	✓			✓			✓			✓			✓	✓
3	WGS (R), WGS (L), CMJ, SSRT (R), SJ, SSRT (L), DCT								3x4	3x5	3x6	3x4	4x5	3x6	

Key: Values are presented as 'sets' and 'reps'. BJ = box jump; CMJ = countermovement jump; DCT = dynamic chest throw; DSRT = dynamic side rotational throw; JOH = jump over hurdles; L = left side; R = right side; S = session; SCT = static chest throw; SSRT = static side rotational throw; SJ = squat jump; WGS = weighted golf swing.

4.4 Statistical Analysis

To assess single-subject research, mixed statistical and visual analyses is the preferred method to determine meaningful changes following training interventions (Kromrey & Johnson, 1996). The single-subject statistical analysis methods include: the split method of trend estimation, the C statistic, and the two-band standard deviation (SD) method. For the purpose of this investigation, the two band SD method was chosen due to its agreement to the C static and split method of trend estimation (Nourbakhsh & Ottenbacher, 1994). This method allows for ease of data interpretation as numerical changes are tracked via graphing with clear set rules to establish substantial change. Two bands are shown on a result graph; upper and lower bands are calculated by pre-testing means ± 2SD. To determine substantial changes, post-test data points must fall outside either band and these changes are strengthened when consecutive or numerous data points fall outside the SD lines (Backman, Harris, Chisholm, & Monette, 1997). Visual analysis primarily observes large change therefore only measures that exceed the ±2SD threshold are of importance (Nourbakhsh & Ottenbacher, 1994).

All statistical analysis was performed in Microsoft Excel (Microsoft, 2016). In addition to the visual analysis the mean pre (mean of three data points) to mid, post and four-week post- intervention (mean of two data points) results are provided for all neuromuscular characteristics and golf drive performance measures. The mean baseline, mid, post and four-week post- changes are provided for the control, experimental, and non-training period for golf drive performance and neuromuscular characteristics measures (raw and % mean change). Therefore, a statistical representation of change is quantified. When interpreting the complete data set conclusions should be determined based on ±2SD graph as misrepresentation of data points can exist when the results are based on numerical tabulated data.

4.5 Results

4.5.1 Driver CHS.

Participant one

Visual analysis revealed a substantial increase in CHS which exceeded the ± 2SD threshold for baseline to mid and baseline to post-testing session (*i.e.* 5.96% and 8.14% respectively) (Table 8). However, a decrease of -2.33% in CHS occurred between the post-intervention and four-week post-intervention testing sessions (Figure 11).

Participant two

Visual analysis revealed a substantial increase in CHS which exceeded the ± 2SD threshold for baseline to mid and baseline to post-testing session (*i.e*. 5.35% and 6.41% respectively) (Table 8). However, a decrease of -2.1% in CHS occurred between the post-intervention and four-week post-intervention testing sessions (Figure 11).

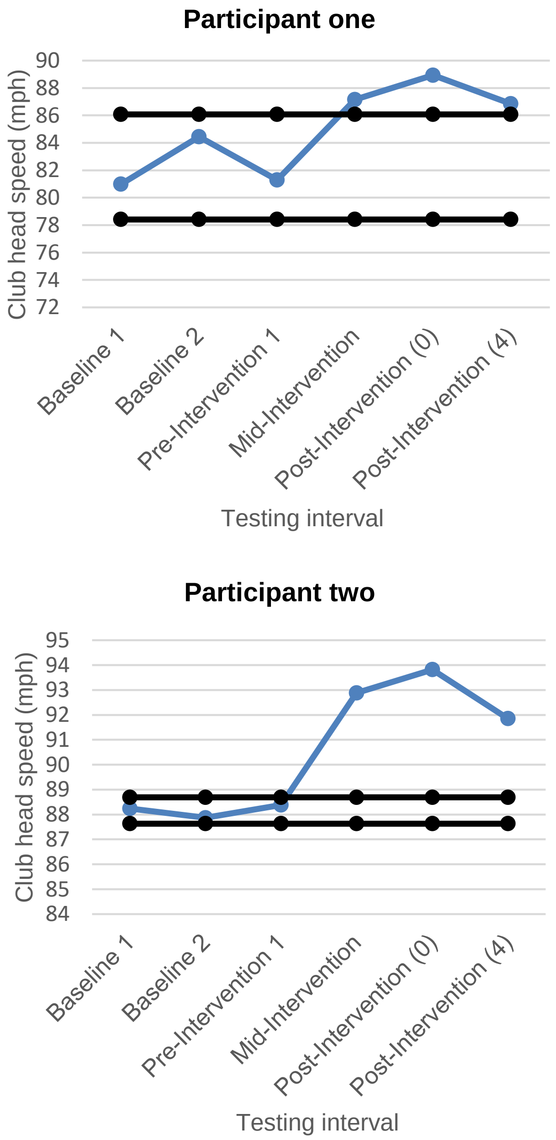


Figure 11. Driver CHS pre-to post-change.

Table 8

Mean Pre- to Post-change in CHS

		Pre (Baseline)	Mid	Post	Post (4 weeks)	% change			
						Baseline to Mid	Baseline to Post	Baseline to four-week post-intervention	Post to four-week post-intervention
P1	CHS	36.76 ± 0.85 m/s (82.24 ± 1.91 mph)	38.97 ± 0.34 m/s (87.15 ± 0.8 mph)	39.74 ± 0.58 m/s (88.94 ± 1.31 mph)	38.83 ± 0.48 m/s (86.86 ± 1.07 mph)	5.96	8.14	5.61	-2.33
P2	CHS	39.41 ± 0.11 m/s (88.16 ± 0.26 mph)	41.52 ± 0.54 m/s (92.87 ± 1.21 mph)	41.87 ± 0.38 m/s (93.81 ± 1.09 mph)	41.06 ± 0.78 m/s (91.84 ± 1.74 mph)	5.35	6.41	4.18	-2.1

Key: P = participants.

4.5.2 Upper-body power.

Participant one

There was a substantial increase in all upper-body measures (*i.e.* static chest throw, dynamic chest throw, static side rotational throw right and left, dynamic side rotational throw right and left) which exceeded the ± 2SD threshold from baseline to post-intervention testing sessions (Table 9). However, all upper-body measures decreased between the post to four-week post-intervention time points (Figure 12).

Participant two

There was a substantial increase in all upper-body measures (*i.e.* static chest throw, dynamic chest throw, static side rotational throw right and left, dynamic side rotational throw right and left) which exceeded the ± 2SD threshold from baseline to post-intervention testing sessions (Table 9). However, all upper-body measures decreased between the post to four-week post-intervention time points (Figure 12).

Participant one

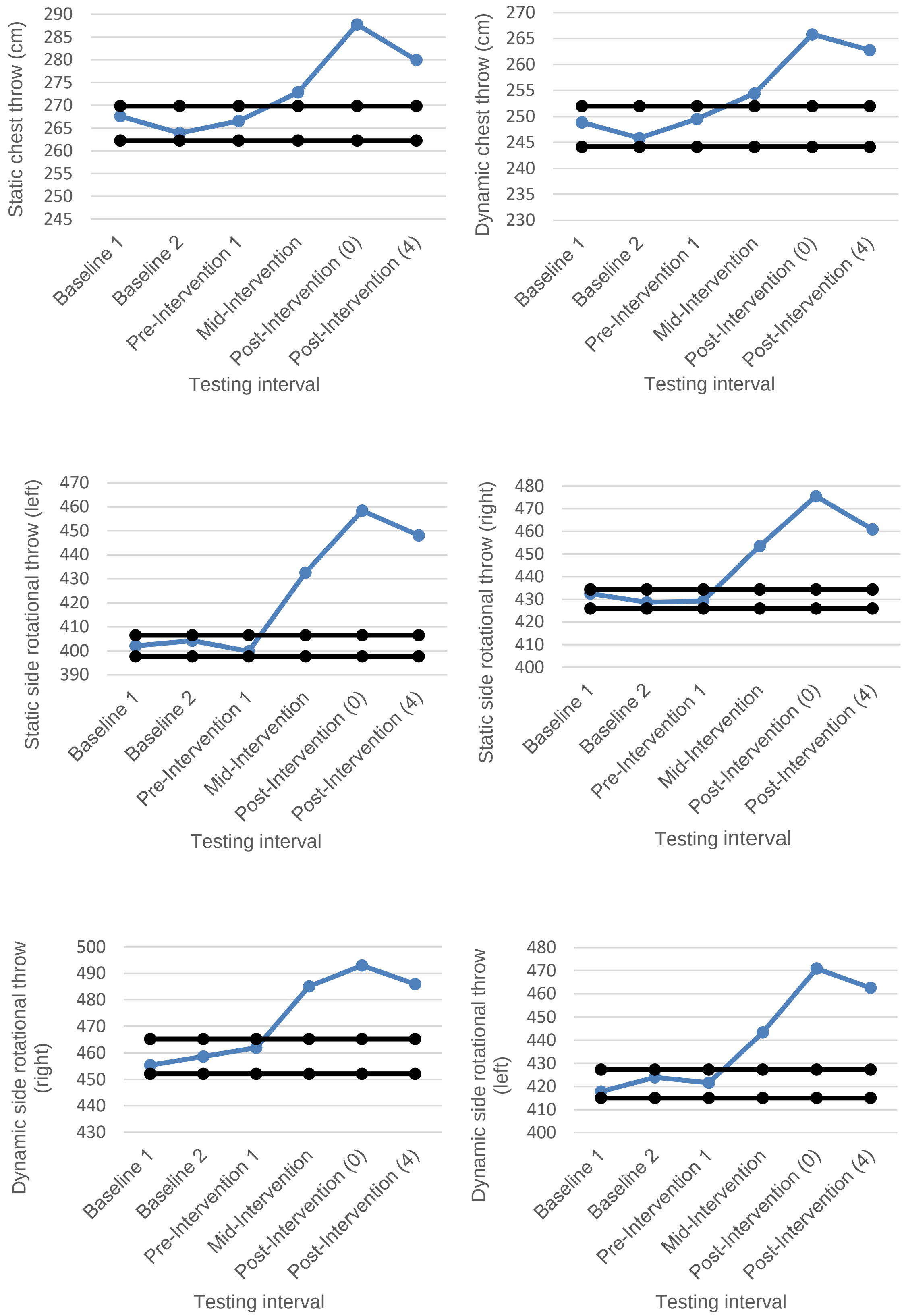


Figure 12. Upper-body power measures pre-to post-change. (continued over page)

Participant two

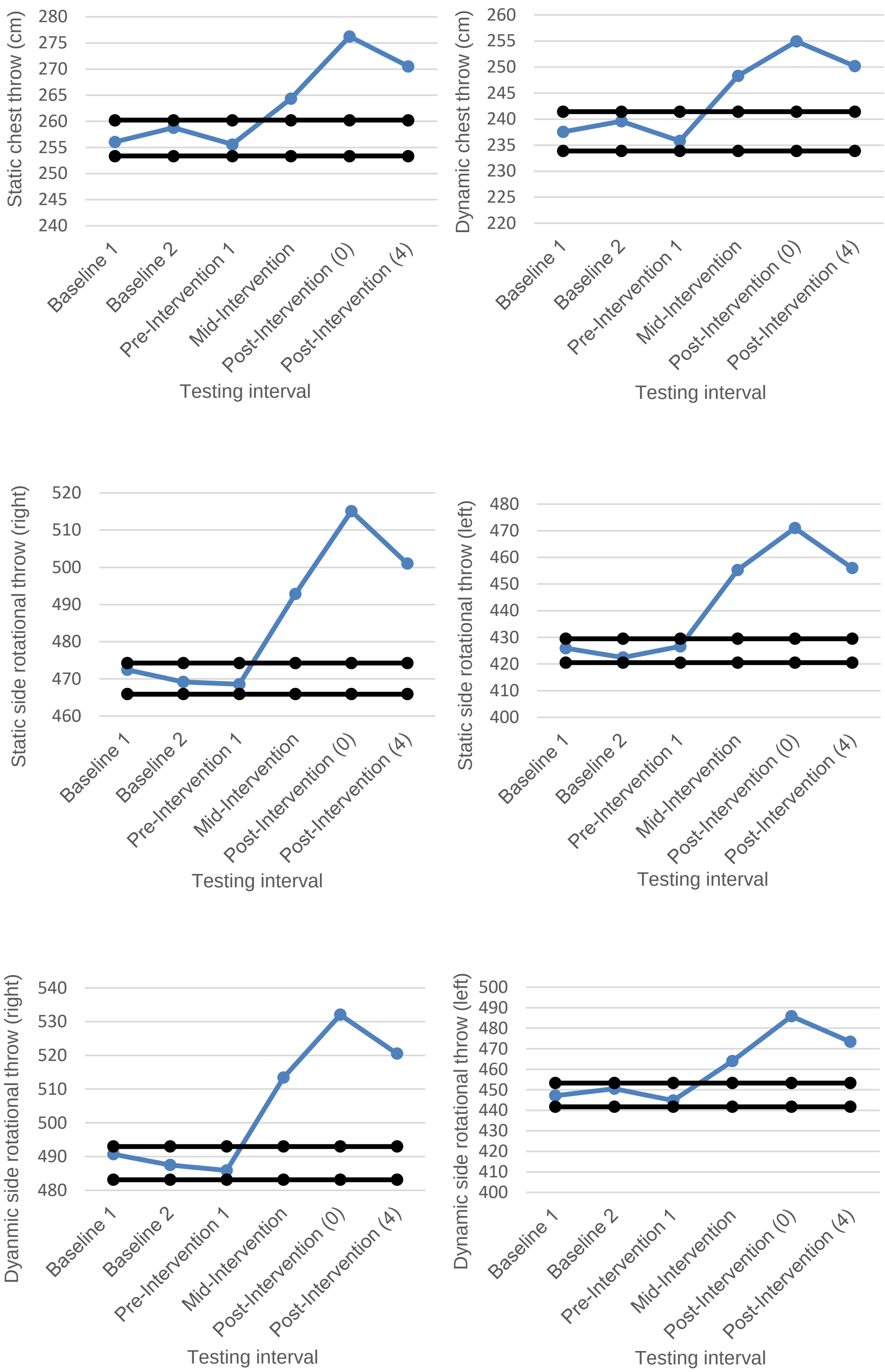


Figure 12. Upper-body power measures pre-to post-change.

Table 9

Mean Pre- to Post-change in Upper-body Power Measures

		Pre (Baseline)	Mid	Post	Post (4 weeks)	% change			
						Baseline to Mid	Baseline to Post	Baseline to four-week post-intervention	Post to four-week post-intervention
P1	SCT	266.03 ± 1.9	272.83 ± 2.78	287.43 ± 2.54	279.95 ± 2.31	2.55	8.17	5.23	-2.7
	DCT	248.08 ± 1.95	254.45 ± 2.94	265.84 ± 2.25	260.79 ± 2.18	2.56	7.15	5.92	-1.14
	SSRT (R)	430.16 ± 2.1	454.45 ± 2.94	473.5 ± 3.05	460.93 ± 2.32	5.41	10.53	7.15	-3.06
	SSRT(L)	402.00 ± 2.22	435.92 ± 2.61	464.07 ± 2.65	453.98 ± 2.15	7.6	14.03	11.43	-2.27
	DSRT (R)	458.64 ± 3.29	491.72 ± 2.65	498.94 ± 2.55	492.61 ± 3.01	5.75	8.25	5.96	-1.4
	DSRT (L)	421.08 ± 3.07	453.26 ± 2.65	480.92 ± 2.0	472.61 ± 2.26	5.26	11.83	9.86	-1.76
P2	SCT	256.80 ± 1.71	264.36 ± 2.58	276.24 ± 2.59	270.56 ± 2.44	2.94	7.56	5.35	-2.05
	DCT	237.65 ± 1.88	248.31 ± 2.07	254.93 ± 2.0	250.85 ± 2.31	4.48	7.27	5.31	-1.86
	SSRT (R)	470.07 ± 2.09	492.79 ± 3.64	516.11 ± 3.01	500.99 ± 2.62	4.83	9.58	6.57	-2.74
	SSRT(L)	425.00 ± 2.23	451.96 ± 3.6	471.67 ± 2.61	455.99 ± 2.64	7.12	10.82	7.29	-3.18
	DSRT (R)	488.04 ± 2.46	513.39 ± 3.30	532.01 ± 2.13	520.53 ± 2.2	5.19	9.01	6.65	-2.15
	DSRT (L)	447.48 ± 2.89	463.96 ± 3.44	485.81 ± 2.97	473.35 ± 2.94	3.68	8.56	5.77	-2.56

Key: All throws was measured in cm. DCT = dynamic chest throw; DSRT = dynamic side rotational throw; L = left; P = participant; R = right; SCT = static chest throw; SSRT = static side rotational throw.

4.5.3 Lower-body power.

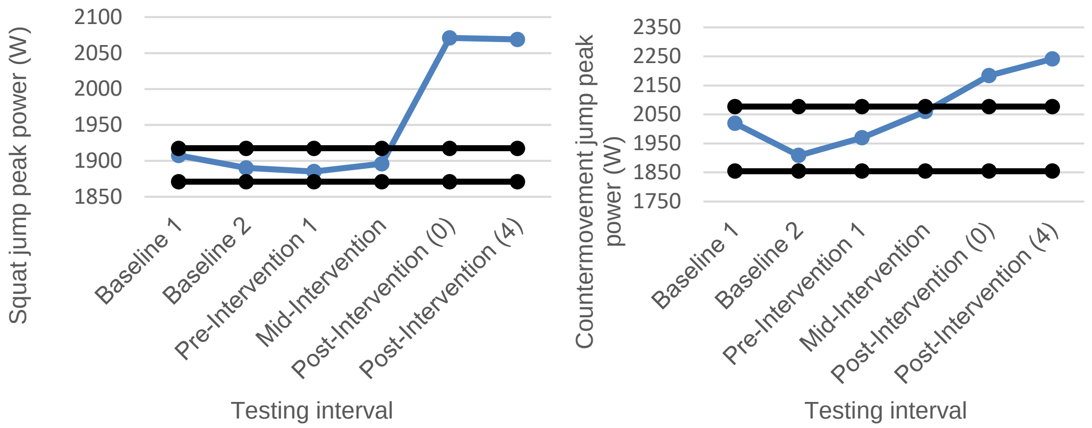
Participant one

There was a substantial increase in SJ peak power post-intervention (9.32%) and four weeks post-intervention (9.22%) which exceeded the ±2SD threshold. However, a decrease of -0.098 % was reported for SJ peak power between post to four-week post-intervention. There was a substantial increase in CMJ peak power post-intervention (11.07%) and four-week post-intervention (14.01%) which exceeded the ±2SD threshold (Table 10). Additionally, an increase of 2.64% was reported for CMJ peak power between the post-intervention to four-week post-intervention (Figure 13).

Participant two

There was a substantial increase in SJ and CMJ peak power post-intervention and four-week post-intervention which exceeded the ± 2SD threshold. An increase in SJ peak power was reported in the post-intervention (7.14%) and four-week post-intervention (11.21%) (Table 10). Additionally, an increase in CMJ peak power was reported at mid-intervention (6.32%), post-intervention (8.59%) and four-week post-intervention (11.53%) (Figure 13).

Participant one



Participant two

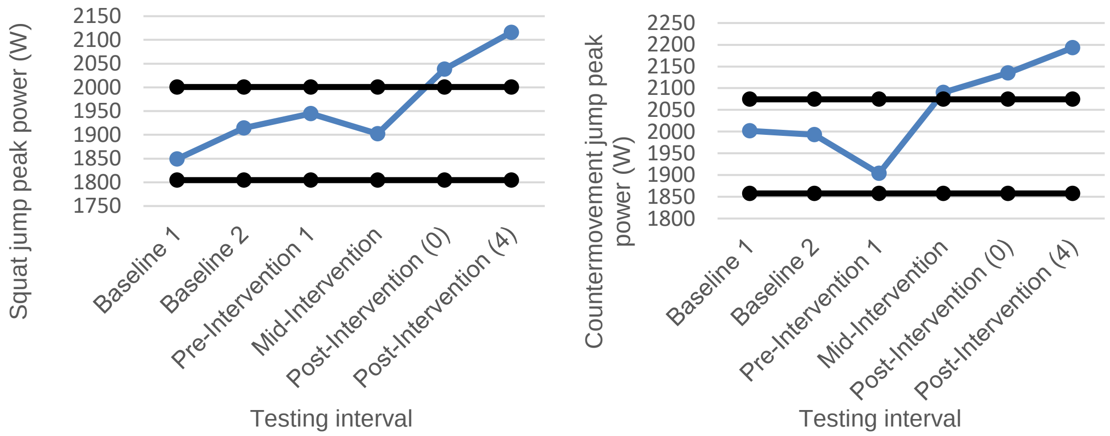


Figure 13. Lower-body power measures pre-to post-change.

Table 10

Mean Pre- to Post-Change in Lower-Body Peak Power Measure

		Pre (Baseline)	Mid	Post (0 week)	Post (4 weeks)	% change			
						Baseline to Mid	Baseline to Post	Baseline to four-week post-intervention	Post to four-week post-intervention
P1	SJ	1894.28 ± 11.63	1896.13 ± 69.33	2071 ± 40.75	2068.97 ± 69.02	0.097	9.32	9.22	-0.098
	CMJ	1965 ± 55.70	2060.62 ± 21.51	2183.54 ± 46.84	2241.28 ± 49.12	4.82	11.07	14.01	2.64
P2	SJ	1902.71 ± 49.04	1902.4 ± 30.49	2038.6 ± 19.86	2116.1 ± 87.09	-0.01	7.14	11.21	3.8
	CMJ	1966.03 ± 54.14	2090.35 ± 6.41	2135.10 ± 45.62	2192.82 ± 30.83	6.32	8.59	11.53	2.7

Key: Peak power was measured in N.m/s. CMJ = countermovement jump; P = participants; SJ = squat jump.

4.6 Discussion

Increases in CHS following a six-week ballistic and plyometric training protocol, with a percentage change of 8.14% and 6.41% post-intervention, were observed for participant one and two, respectively (Table 8). A substantial increase was reported for upper- and lower-body measures of power for both participants. Following the four-week post-intervention period, both participants demonstrated a decrease in CHS and all upper-body power measures while lower-body power increased. Despite the decrease in CHS between the post-testing and four-week post testing data points, a substantial increase in CHS (relative to pre-testing) remained following the six-week ballistic and plyometric training programme for highly-skilled female golfers. To the authors knowledge this is the first study to determine the effects of a six-week ballistic and plyometric training programme on female golfers' drive performance and neuromuscular characteristics

4.6.1 Golf drive performance. Golf drive performance measure (*i.e.* CHS) showed substantial increases from pre-to post-training for both participants (Table 8). Although, there was a decrease in CHS four-week post-intervention period, a substantial increase (relative to pre-testing) remained following the ballistic and plyometric training programme for both participants. Improvements in drive distance were most likely due to an improvement in neuromuscular characteristic performances (*i.e.* upper- and lower-body power measures). Proper swing mechanics and minimal changes in swing mechanics is important to maintain throughout the training programme as it decrease the possibility for changes in CHS to be attributed by major changes in swing mechanics (Newell, 2001). Therefore, participants were informed to not make any major changes to swing mechanics throughout this training programme. Previous authors have found improvements in neuromuscular characteristics improved the rotational velocity of thorax, pelvis segments and X-factor, and consequently increased CHS post resistance training programme in male golfers (Ghigiarelli et al., 2015; Lephart et al., 2007). However, biomechanical analysis was not measured in this research study to determine changes in swing mechanics between pre- to post training. Therefore, it is uncertain whether changes in swing mechanics occurred throughout this training programme on highly-skilled female golfers and the effects on CHS.

4.6.2 Upper-body power. The static and dynamic side rotational throws showed the greatest improvement in upper-body power compared to the static and dynamic chest throws. However, the static rotational side throw (right and left) showed greater improvement in upper-body power compared to the dynamic rotational side throw (right and left) for the testing sessions (*i.e.* pre- to mid and post-testing). There was a decrease in all upper-body power measures four-week post-testing. Thus, it is possible that the decrease in upper-body power measures may have contributed to the decrease in CHS four-week post-testing. The ability to produce rotational power in both the left and right sides may contribute to increases in CHS (Alvarez et al., 2012; Ghigiarelli et al., 2015). As both participants were right handed golfers, there was a difference between static and dynamic rotational throws in the right side compared to the left side of the body in the baseline testing session. The greatest improvement was shown in left side for static rotational throws compared to the right side as shown in mid and post testing sessions (Table 9). The intention to move a load as fast as possible can influence force-velocity adaptation which may primarily be due to increase in velocity and thus CHS (Blazevich & Jenkins, 2002). Therefore, improvements in upper-body symmetry and the ability to utilise rotational power in the left side for a right-handed golfer may contribute to increases in CHS and thus golf drive performance for highly-skilled female golfers. Previous investigators have described the golf swing as a ballistic action due to the short transition time between the backswing and the follow-through for skilled male golfers (Bliss et al., 2015; Fletcher & Hartwell, 2004). The greatest improvement in upper-body power for both participants was the static side rotational throw compared to the dynamic side rotational throw. However, it is uncertain whether exercises that minimise the utilisation of SSC may contribute to greater improvements in CHS compare to exercises that promote SSC, therefore further research is warranted. It is possible that highly-skilled female golfers' golf swing requires a slower SSC allowing an increase in time for cross-bridge formation during the backswing to generate high CHS (Hegedus et al., 2016; Keogh et al., 2009; Read, Miller, et al., 2013). Therefore, it is important to incorporate golf-specific ballistic exercises (*i.e.* dynamic and static side rotational throws and weighted golf club swings) to improve CHS.

To improve CHS it is important to incorporate exercises that are similar to the golf swing movement and swing speed for male or female golfers (Keogh et al., 2009; Read, Miller, et al., 2013). There are significant correlation between seated chest throw ($r = 0.67$) (Justin et al., 2012; Read, Lloyd, et al., 2013), side rotational throw ($r = 0.63$) (Bradley et al., 2009; Read, Lloyd, et al., 2013) and CHS. The greatest improvement in upper-body power for both highly-skilled female participants was the static and dynamic side rotational throws compared to the static and dynamic chest throw. The findings in this study on highly-skilled female golfers are similar to findings in a previous study on skilled male golfers. Bliss et al. (2015) found the greatest improvement in dynamic rotational throws (22.9%) compared to chest throws (11.1%) for skilled male golfers (HCP = 4.7 ± 3.0). Therefore, exercises that mimic the golf swing movement contributes to improvements in CHS (0.8 m/s [1.78 mph]) following eight-weeks post ballistic and plyometric training. Thus, increase in SSC and elastic energy improves CHS for skilled male golfers (Bliss et al., 2015). However, the ballistic training for skilled male golfers did not incorporate both static and dynamic rotational throws and static and dynamic chest throws. Therefore, it is uncertain whether static rotational throws contributes to improvement in CHS for skilled male golfers (Bliss et al., 2015).

4.6.3 Lower-body power. Both participants improved their lower-body peak power across all testing occasions with the greatest improvements occurring during the CMJ. Additionally, both participants showed an increase in CMJ in lower-body power four-week post-intervention (Table 10). Previous investigators reported a correlation between CMJ peak power and CHS ($r = 0.61$) (Read, Lloyd, et al., 2013). The sequencing of force transfer of the CMJ (i.e. distal to proximal) is similar to the development and duration of force from ground-up and the duration of the CMJ (>250 ms) and golf drive (290 ms) (Mangus et al., 2006; McTeigue, Lamb, Mottram, & Pirozzolo, 1994; Read, Miller, et al., 2013) . Therefore, increase in lower-body elastic energy and SSC may contribute to increases in CHS for highly-skilled female. Additionally, previous investigators found that SJ was also correlated with CHS (r = 0.53), therefore exercises that focus on concentric muscle action may also contribute to increase in CHS for highly-skilled female golfers (Read, Lloyd, et al., 2013).

The increase in CMJ four-week post-intervention may have contribute to the remaining substantial improvement in CHS for highly-skilled female golfers in this study. Previous investigators reported that the lower-body works predominately in the first phase of the downswing to initiate the X-factor stretch (*i.e*. separation angle between the pelvis and the thorax) (Burden et al., 1998; Leary et al., 2012; Nesbit, 2005). The transition time between the top of the golf swing and the downswing requires the lower-body to rapidly rotate the hips and extend the knee to maximise X-factor stretch for the generation of high CHS (Burden et al., 1998; Leary et al., 2012; Nesbit, 2005). Therefore, the increase in CMJ four-week post-intervention may have contributed to an increase in the X-factor stretch which helped to generate higher CHS for the highly-skilled female golfers (Table 10). Thus, it is important to incorporate plyometric exercises (*i.e.* CMJ, SJ, box jumps and hurdle jumps) to improve CHS.

4.7 Future Studies

Due to the small sample of participants in this research study, future studies are warranted on a larger sample of highly-skilled female golfers with resistance training experience (*i.e.* at least 1 yr) to determine whether female golfers of high skill level show statistically significant improvements in CHS and/or neuromuscular characteristics following six-week ballistic and plyometric training programme. Furthermore, research is required to compare highly-skilled male and female golfers' (*i.e.* HCP < 5, with 1 yr of resistance training, without ballistic and plyometric training in the past) to determine the sex-related differences in ballistic and plyometric training on golf drive performance (*i.e.* CHS) and neuromuscular characteristics (*i.e.* upper- and lower-body power measures). Additionally, swing mechanics were not measured post-testing in this study, therefore it is uncertain whether improvements in lower-body power measures improved X-factor stretch (*i.e.* separation angle and velocity of thorax and pelvis segment). Therefore, to determine potential changes in swing mechanics throughout a training programme, future studies should analyse biomechanics (via 3D motion capture analysis) of the golf swing to determine changes in thorax and pelvis segments in swing mechanics from pre- to post-resistance training programme.

4.8 Limitations

There are several limitations that exist within this research study. Due to the limited number of female golfers in Auckland region, there was a small sample size of participants recruited in this study. The results of this study can only be generalised to highly-skilled female golfers (HCP < 5) with resistance training experience but without ballistic and plyometric training experience. In addition, as the experimental training intervention was performed during the winter months (golf off-season) there was a decrease in the frequency of weekly golf practice sessions and competitions (*i.e.* regional and national) compared to the competitive season for highly-skilled female participants. It is speculated that the decrease in weekly golf practice may limit the improvement of CHS due to potential increases in endpoint movement variability of the swing mechanics which may affect both CHS and ball striking at impact.

4.9 Conclusion

The substantial improvements in drive performance (*i.e.* CHS) was likely due to the inclusion of golf-specific exercises that are similar to the golf swing movement and swing speed for highly-skilled female golfers. The static side rotational throw reported the greatest improvement in all testing sessions (*i.e*. mid, post and four-week post) compared to the dynamic rotational throw. Therefore, exercises that minimise the utilisation of SSC may contribute to improvements in CHS. It is possible that the golf swing of highly-skilled female golfers requires a slower SSC which allows an increased time for cross-bridge formation during the backswing to generate high CHS. Additionally, CMJ showed the greatest improvement in peak power compared to SJ in all testing sessions (*i.e.* mid, post and four-week post). Following the four-week post-intervention period there was a decrease in golf drive performance (*i.e.* CHS) and all upper-body power measures for both participants. However, the increase in CMJ four-week post- intervention may contribute to the remaining increase in CHS relative to pre-testing due increase in lower-body elastic energy and SSC which may have increased in X-factor stretch.

Ballistic and plyometric training over six weeks appears to be an appropriate training method to improve drive performance and neuromuscular characterises in highly-skilled female golfers (HCP < 5). Thus, coaches and practitioners should incorporate upper-and lower-body dynamic (*i.e.* utilisation of SSC) and static (*i.e.* with a 3 s pause on the eccentric phase to minimise the utilisation of SSC) ballistic and plyometric exercises in golf-specific training programmes as they both contribute to improvement in CHS for highly-skilled female golfers (HCP < 5).

Chapter Five:

Summary, future research and limitations

5.1 Summary

Resistance training programmes have become an alternative method to increase CHS as golfers seek methods to increase their drive distance which will lead to a greater likelihood of a reduction in their total score. The majority of resistance training programmes currently consist of strength, flexibility, functional movement and power type (*e.g.* plyometric and ballistic) protocols for male golfers to improve drive performance and neuromuscular characteristics. However, very little is known on the effects of ballistic and plyometric training on drive performance and neuromuscular characteristics on female golfers.

To maximise CHS, the ability to generate rotational velocity is essential as it differentiates between high and low CHS for male and female golfers (S. J. Brown et al., 2011; Chu et al., 2010; Okuda et al., 2010). As such, biomechanical evaluations of the golf swing (3D motion capture) and CHS have been performed pre- to post-resistance training programmes. Unfortunately, 3D motion capture cannot be used in a field-based environment to measure rotational velocity of the golf swing. Additionally, according to the kinematic sequencing of the golf swing, the release of the wrist is the last body segment to transfer rotational velocity to the golf club at ball impact. Therefore, the first investigation (Chapter Three) sought to quantify the reliability of an IMU to measure the rotational velocity of a golf drive. The CHS (as determined by Flightscope launch monitor) was observed to be a reliable measure (CM = -0.18%, CV < 10%, ICC = 0.98) of golf drive performance. However, rotational velocity (as determined by IMU) demonstrated a poor level of reliability and high variability between trials (CM = -17.59%, CV > 10%, ICC = 0.92). All skilled female golfers recruited in this study had a HCP of ≤ 10. However, the differences in neuromuscular characteristics (*i.e.* golfers with and without resistance training experience) and age (range = 18-61 years old) may have contributed to the large variation in mean and standard deviation of rotational velocity and poor reliability. Therefore, the IMU placed on the lead wrist to measure rotational velocity of the golf drive was found not to be reliable in this study and further research is required before it should be utilised as a means to quantify pre- to post-change in rotational velocity of the golf drive.

In Chapter Four, a six-week ballistic and plyometric training protocol was undertaken involving two highly-skilled female golfers (HCP < 5) to determine the effects on drive performance (CHS) and neuromuscular characteristics (*i.e.* upper- and lower-body peak power). Golf drive performance and neuromuscular characteristics measures were assessed on six occasions (weeks 0, 3, 6, 9, 12 and 16) over a 16-week period (*i.e.* six-week pre-intervention [control], six-week intervention [experimental] and four-week post-intervention [non-training] period). A six-week ballistic and plyometric training intervention elicited a substantial improvement in drive performance (CHS) in highly-skilled female golfers. Additionally, static side rotational throws reported the greatest improvement in all testing sessions compared to the dynamic side rotational throws. The CMJ showed the greatest improvement in peak power compared to SJ in all testing measures. Thus, the substantial improvements in upper- and lower-body power measures were transferred to golf performance as seen in the increase in CHS for both participants. Following a four-week post-intervention period, there was a decrease in golf drive performance (CHS) and all upper-body power measures for both participants. However, there was also an increase in lower-body power (*i.e.* CMJ) following the four-week post-intervention period for both participants. It is possible that decrease in CHS may be due to the decrease in upper-body power measures. Therefore, it would seem that the remaining substantial improvements in upper- and lower-body power measures were transferred to golf performance as seen in the improvement in CHS for both participants. Ballistic and plyometric training over six weeks would seem an appropriate method of training to improve drive performance and neuromuscular characterises in highly-skilled female golfers (HCP < 5).

5.2 Future research

Future research is required on a larger, homogenous sample size of skilled female and/or male golfers (HCP ≤ 10) with similar age group (*i.e.* younger participants < 30) and resistance training experience (*i.e.* at least 1 yr) to determine the reliability of the IMU placed on the wrist to measure rotational velocity of the golf drive. Additionally, future studies are warranted on a larger sample of highly-skilled female golfers with resistance training experience to determine whether female golfers of high skill level show statistically significant improvements in CHS and/or neuromuscular characteristics post six-week ballistic and plyometric training programme. Female golfers of various skill levels (*i.e.* less refined swing mechanics, increase in swing variability and HCP ≥ 11) were not recruited in the ballistic and plyometric resistance training intervention therefore the effects on this group require investigation. Furthermore, further research is required to compare highly-skilled male and female golfers' (*i.e.* HCP < 5, with 1 yr of resistance training, without ballistic and plyometric training in the past) to determine the sex-related differences in ballistic and plyometric training on golf drive performance (CHS) and neuromuscular characteristics (upper- and lower-body power measures). To determine potential changes in swing mechanics throughout a golf training programme, future studies should analyse biomechanics (via 3D motion capture analysis) of the golf swing to determine changes in thorax and pelvis segments in swing mechanics from pre- to post-resistance training programme.

5.3 Limitations

There are several limitations specific to the reliability of the IMU to measure the rotational velocity of the golf drive. In the present investigation, the IMU was only placed on the lead wrist to determine the lead wrist rotational velocity. However, it does not provide further information on the changes in rotational velocity of the thorax segment and/or pelvis. Therefore, to determine the golf swing kinematic sequence of the different body segments (*e.g.* thorax and pelvis) further research is required on highly-skilled golfers. Additionally, all female participants utilised their own golf club (*i.e.* driver) therefore, the golf equipment was not standardised as changes in golf equipment may disrupt swing mechanics resulting in changes to CHS and/or rotational velocity measures (Myers et al., 2008). Furthermore, environmental factors (*e.g.* wind, rain, grass conditions) and differences in golf balls can result in changes to the total drive distance measured using the Flightscope launch monitor. Therefore, only CHS was used as a measure of golf drive performance (Fletcher & Hartwell, 2004). A correlation between CHS and rotational velocity was not determined due to the small sample size of female golfers and the restricted HCP criteria (*i.e.* HCP ≤ 10) and further research is warranted in this area. Lastly, as the current reliability study only included female participants, the findings cannot be generalised to male golfers.

Due to the limited number of female golfers in Auckland region, there was a small sample size of participants recruited in this study. The results of this study can only be generalised to highly-skilled female golfers (HCP < 5) with resistance training experience but without ballistic and plyometric training experience. In addition, as the experimental training intervention was performed during the winter months (golf off-season) there was a decrease in the frequency of weekly golf practice sessions and competitions (*i.e.* regional and national) compared to the competitive season for highly-skilled female participants. It is speculated that the decrease in weekly golf practice may limit the improvement of CHS due to potential increases in endpoint movement variability of the swing mechanics which may affect both CHS and ball striking at impact.

5.4 Delimitations

The study on the reliability of an IMU to measure the rotational velocity of a golf drive was able to determine that there are many factors (*i.e.* age, resistance training experience) that influence the rotational velocity of the wrist, despite the skill level of the golfers in question (HCP ≤ 10). There are several strengths that exist within the study on the effects of a six-week ballistic and plyometric training programme on female golfers' drive performance and neuromuscular characteristics. Due to the limited number of highly-skilled female golfers (HCP < 5) recruited in the study, the researcher could provide one-on-one training sessions to each participant to ensure the ballistic (*e.g.* dynamic and static chest throw and side rotational throws) and plyometric exercises (*e.g.* CMJ, SJ, box jump and hurdle jumps) were performed with the correct technique throughout all training sessions. Additionally, due to the inclusion of the golf- specific exercises (*i.e.* weighted golf sticks) and the ballistic movements (*i.e.* side rotational throws) that mimic specific phases of the golf swing (backswing, downswing and follow-through) it was important to ensure that the exercises were performed with the correct sequencing of movement to prevent any negative transference effects to swing mechanics. Highly-skilled female golfers (HCP < 5) were recruited for this investigation due to their refined swing mechanics and low endpoint movement variability to minimise the potential effects of changes in swing technique. Additionally, the participants were informed to not intentionally make any technical refinements to their swing mechanics throughout the duration of this study. Therefore, the observed changes in golf drive performance following the training intervention were less likely to be due to conscious changes in swing mechanics. Finally, the single subject design allowed a greater number of training and testing sessions to be performed which provides researchers, coaches and practitioners with a understanding of the changes in neuromuscular and golf drive performance throughout a greater intervention period (*i.e.* pre-intervention [control], post-intervention [experimental] and four-week post-intervention [non-training]).

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Appendix A: Ethics Approval

AUTEC Secretariat

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29 March 2017

Adam Storey
Faculty of Health and Environmental Sciences

Dear Adam

Re Ethics Application: **17/41 The effects of eight-week training programme of plyometric and ballistic exercises on female golfers' physical characteristics and drive performance**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 29 March 2020.

As part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 29 March 2020;
- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 29 March 2020 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.
All the very best with your research,

Kate O'Connor
Executive Secretary
Auckland University of Technology Ethics Committee

Appendix B: Participant Information Sheet

Participant Information Sheet

Date Information Sheet Produced:

29/03/2017

Project Title

The effects of a six-week ballistic and plyometric training programme on female golfers' drive performance and neuromuscular characteristics

An Invitation

You are invited to participate in the above research that will be conducted by Miss Anita Ya Ting Chau (researcher) and supervised by Dr. Adam Storey (primary supervisor) and Dr. Scott R. Brown (secondary supervisor). Your participation in this research/investigation is completely voluntary. Your participation to the research study will contribute to the researcher's Master's thesis in Sport and Exercise Science, potential publication in journal articles, conferences and presentations. Your decision to participate or not participate will not affect any relationship with the researcher or supervisors now or in the future.

What is the purpose of this research?

The golf swing requires high-velocity rotational movement of the upper extremities, trunk and core musculature while the lower extremities are utilized as a stable base of support and generation of ground reaction force for club head speed (CHS). Resistance training programmes comprised of golf-specific exercises have shown to improve CHS and drive distance in male golfers. Previous researchers have shown strong associations between power type exercises and golf CHS in male golfers. However, at present no study has assessed the effects of implementing power based resistance training for female golfers.

Previous investigators have determined Flightscope to be a reliable (ICC = 0.87), accurate and valid system to track CHS changes which is the determinant of golf drive distance and contribute to performance. Previous authors of studies have used a gyroscope to measure rotational velocity of the golf club and golf swing motion by placing the gyroscope on the golf shaft and/or golfers' wrist. However, there is currently no study that has measured the golf drive rotational velocity when an inertial measurement unit (IMU) (which consist of a gyroscope) is placed on the wrist, golf shaft and head of the golf club. Therefore, reliability and validity study of golf drive rotational velocity (IMU) is required to determine whether it can assess golf drive performance.

The purpose of Study 1 is to determine the reliability and validity of the IMU to assess changes in golf drive performance. The purpose of Study 2 is to evaluate the effects of a six-week ballistic and plyometric training programme on female golfers' drive performance (CHS) and neuromuscular characteristics (upper- and lower-body power). The results will add to the current body of golf conditioning literature and contribute towards the researcher's Master's Degree in Sport and Exercise Science. All results will be published into a thesis, journal article and may include a conference presentation.

How was I identified and why am I being invited to participate in this research?

You are eligible and are invited to participate in Study 1 if you; 1) are female aged 16 years old and over, 2) currently have a handicap of 10 or less, 3) have no current acute or chronic injuries and/or medical conditions that may inhibit your participation of the full extent of the testing sessions, and 4) are not using any performance enhancing or banned substances (World Anti-Doping Agency, 2017).

You are eligible and are invited to participate in Study 2 if you; 1) are female aged 16-30 years old, 2) currently have a handicap of less than 5, 3) have no current acute or chronic injuries and/or medical conditions that may inhibit your participation of the full extent of the training programme, 4) are not using any performance enhancing or banned substances (World Anti-Doping Agency, 2017), and 5) have at least one year of general strength and/or any resistance type training experience in the past.

Female golfers fitting either of the inclusion criteria will be identified through postings and to local golf courses, golf clubs and public golf courses. Emails and verbal communication with North Harbour Golf Association, Auckland Golf Association and New Zealand Professional Golf Association in Auckland. Exclusion criteria are golfers with any current injury, illness or health issue that may limit the participation of the study and does not fit the inclusion criteria.

If you fit the inclusion criteria, please read the sections in the information sheet that apply to you and the details related to the specific study.

How do I agree to participate in this research?

Your participation in this research is voluntary (it is your choice) and whether or not you choose to participate will neither advantage nor disadvantage you. If you agree to participate, a consent form will be email to you to read and requires your signature. You are able to withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal of your data may not be possible.

What will happen in this research?

Study 1: If you are eligible and have given voluntary consent to participate, you will be asked to attend two testing sessions, separated by 1 week and anthropometric data (height, weight, age, golf handicap) will be collected during session 1. All participants will be required to hit 10 maximal golf drives in the two testing sessions with an IMU attached. The IMU is small, light-weight and contains a gyroscope which can measure rotational velocity. The Flightscope launch monitor will be used to measure CHS at the same time as the IMU.

<u>Study 2:</u> If you are eligible and have given voluntary consent to participate, you will be asked to attend all baseline testing sessions, training intervention and the post testing sessions. A familiarisation session will be given to all participants for all specific testing protocols and testing equipment before the first baseline testing session. All testing sessions will involve; 1) golf-specific tests (as outlined above in Study 1) and 2) neuromuscular tests which will include upper-body power (forward and rotational throws using medicine balls) and lower-body power measures (vertical jumps using force platform).

<u>Study 2 Overview:</u>

A single-subject design will be used for this training intervention with subjects allocated to a six-week control/baseline period, six-week experimental period followed by a four-week post-intervention period. The aim of the experimental period is to assess the effects of six-week of ballistic and plyometric training on female golfers' golf drive performance and neuromuscular characteristics. Six testing sessions will be performed in total on weeks 1, 3, 6, 9,12 and 16 during the control, experimental and post-intervention period. All participants will be assessed for both drive performance (CHS and rotational velocity) and neuromuscular characteristics measures (upper- and lower-body power measures). Anthropometric data (height, weight, age) will be collected during the testing sessions. During the six-week control period, the participants will continue with their regular golf training and no ballistic and plyometric training programme will be performed. During the six-week experimental period, the participants will continue with their regular golf training and golf competitions, and participants will be doing the prescribed ballistic and plyometric training programme. During the four-week post-intervention period, the participants continue with their regular golf training and golf competitions requirement without performing ballistic and plyometric training to determine the effects on drive performance and neuromuscular characteristics.

Training

Study 1: There is no training sessions involved.

Study 2: The participants in the experimental period will perform the training three times per week for six weeks. Each training session will last approximately 1 hour and 30 minutes in duration. The exercises will be performed in an explosive fashion with moderate to high intensity. These exercises have been chosen due to the strong correlation with golf CHS and have been previously reported to increase CHS and drive distance for male golfers. During the experimental period, the participants will perform the ballistic and plyometric exercises and the exercises will progressively increase throughout the training intervention in volume (sets and reps) in a safe manner to prevent injury and ensure adequate training stimulus. The total volume (sets and reps) will differentiate between heavy and light weeks. A "deloading week" (i.e. reduction in training volume) will be implemented every fourth week to allow for recovery. You will be encouraged to continue with normal golf practices.

What are the discomforts and risks? The level of discomfort and risk during Study 1 and/or Study 2 will be no greater than that experience by participants during their regular golf practice and/or resistance training session. Physical activity and/or training programme has the potential to cause fatigue and possible muscle soreness can occur 12-48 hours following testing and training sessions. However, this is only an acute response to the exercises performed and will subside. This response due to regular golf practice and/or resistance exercises is no different to what participants may experience when it is taken outside of this research project. All participants are able to talk to primary researcher privately if they are feeling any physical discomfort due to their menstrual cycle to ensure all participants feel comfortable during the training sessions, testing sessions and throughout the research project.

How will these discomforts and risks be alleviated?

These physical discomfort and risks during Study 1 and/or Study 2 can be alleviated by proper warm up, cool down and stretching exercises which will be provided by the researcher. Adequate sleep and a balanced nutritional diet is recommended. It is recommended that all participants try to sleep between 8-10 hours per night. Female participants may feel physical discomfort during menstrual cycle therefore the training programme and/or testing intensity (percentage of physical exertion) can be decreased accordingly. All participants are advised to exclude any intense cardiovascular type exercise and other form of resistance training during the training intervention.

What are the benefits?

All participants will receive a personal profile of their golf drive performance (CHS and rotational velocity) and neuromuscular characteristics (upper- and lower-body power measures). Additionally, you will have an expert strength and conditioning coach who will prescribe and supervise all ballistic and plyometric training sessions to ensure all exercises are performed with correct technique. Therefore, it is likely that your golf drive performance measures neuromuscular characteristics will improve.

What compensation is available for injury or negligence?

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my privacy be protected?

All information collected for the purpose of this research will be stored on a secure database accessible by only Anita Ya Ting Chau (researcher), Dr. Adam Storey (primary Supervisor), and Dr. Scott R. Brown (secondary Supervisor). All participants' identity will remain protected and confidential throughout the research through coding for each participant. All information will be stored securely and password protected, and will only be used for the purposes of the research. The privacy of the participants will be protected by allocating unique identification codes to all data. All the data will exclude participants' names to ensure that any data published or otherwise disseminated can in no way lead back to the participants. All data collected from this study will be kept indefinitely in the Sport Research Institute New Zealand (SPRINZ) database (AUT University). All data collected in this research and publications will be kept for six years. Due to the small sample size (i.e. the requirement of skilled level female golfers, past resistance experience and restricted ages), the participants may know of each other from previous golf competitions and socialisation in the golf community in Auckland. Therefore, full confidentiality cannot be given among the participants. However, any data that will be used for the purposes of this thesis, subsequent publications, presentations, and/or further investigations in the future will be encoded in such a way that it will not be possible to identify participants' data in any publication from this work (i.e. all data will be de-identified and aggregated).

What are the costs of participating in this research?

There are no financial costs associated with participating in this research study. However, this is a time cost.

Study 1 will take approximately 15 minutes for each participant per session. Therefore, there will be a total of 30 minutes for two testing sessions.

Study 2 will take one hour and half for all participants for both golf drive performance and neuromuscular characteristics testing session. There will be total of six testing sessions (9 hours) throughout the project. The training programme will consist of three training sessions per week, one hour and half per training session for six-week in total for all participants. There will be a total of 27 hours of training per person. There will be a total of 36 hours required of the participants, which includes the duration of the testing sessions (9 hours) and experimental training sessions (27 hours) for the research project.

What opportunity do I have to consider this invitation?

You have two weeks to consider this invitation. If you do decide to participate in Study 1 and/or Study 2 training programme you will need to fill in an informed voluntary consent form which can be obtained from the researcher.

Will I receive feedback on the results of this research?

All participants will receive personal profile with all their data on golf drive performance (CHS and rotational velocity) neuromuscular characteristic (upper- and lower-body power) measures throughout the research project. This can be provided to any participants who are interested via their personal email. Participants will only receive information in regard to their own results as forms of their personal feedback.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor: Dr. Adam Storey, adam.storey@aut.ac.nz, 0212124200

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, Kate O'Connor, ethics@aut.ac.nz , 921 9999 ext 6038.

Whom do I contact for further information about this research?

Please keep this Information Sheet and a copy of the Consent Form for your future reference. You are also able to contact the research team as follows:

Researcher Contact Details:

Primary Researcher

Anita Ya Ting Chau BSr, PGd, (Masters Student)

AUT-Millennium, 17 Antares Place, Mairangi Bay

0210586077

nita_chau1@hotmail.co.nz

Project Supervisor Contact Details:

Primary Supervisor

Dr. Adam Storey

AUT-Millennium, 17 Antares Place, Mairangi Bay

0212124200

adam.storey@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee (Ethics number 17/41).

Appendix C: Consent Form

Consent Form

Project title: The effects of six-week training programme of ballistic and plyometric exercises on female golfers' drive performance and neuromuscular characteristics.

Project Supervisor: Dr. Adam Storey

Researcher: Anita Ya Ting Chau

○ I agree to participate in Study 1

○ I agree to participate in Study 2

○ I have read and understood the information provided about this research project in the Information Sheet dated 29/03/2017.

○ I have had an opportunity to ask questions and to have them answered.

○ I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.

○ I understand that if I withdraw from the study then I will be offered the choice between having any data or tissue that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.

○ I am not suffering from any acute or chronic injuries

○ I do not have any illness or health issue that may limit the participation to the full length of the study

○ I am not using any performance enhancing or banned substances (World Anti-Doping Agency 2014)

○ I agree to provide data on neuromuscular and golf performance for all testing sessions.

○ I wish to receive a summary of the research findings (please tick one): Yes○ No○

○ I wish to have my data collected from neuromuscular and/or golf performance testing sessions return to me as an individual testing profile (please tick one): Yes○ No○

○ I agree to have the all data collection stored at Sport Research Institute of New Zealand database

Participant's signature:

....

Participant's name:

....

Participant's Contact Details (if appropriate):

………………………………………………………………………………………..

Note: The Participant should retain a copy of this form

Approved by the Auckland University of Technology Ethics Committee (Ethics number 17/41).