Effects of a Weighted Club Warm-Up on Golfing Performance and Biomechanics

A thesis

submitted in fulfilment

of the requirements for the degree

of

Master of Health, Sport and Human Performance

at

The University of Waikato

by

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THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

2019

Abstract

Increasing financial incentives associated with tournament results in golf has led to players, coaches, and sport scientists researching different methods of enhancing performance, especially for the long game (> 91.44 m or 100 yards). Indeed, golfing performance has become increasingly reliant on long game performance due to developments in technology, equipment, physical preparation, and golf swing biomechanics. Golfers are using a variety of warm-up strategies to improve driving performance, including the use of weighted equipment. SuperSpeed Golf™ incorporates the use of differing weighted clubs in a golf-specific warm-up, claiming to enhance clubhead speed for up to 30 minutes post use. SuperSpeed Golf™ asserts that over 600 Professional Golfers Association (PGA) players are currently using the product. Although post activation potentiation and overspeed training literature is cited in support of the use of weighted implements in ball striking sports, there is currently a lack of scientific evidence to substantiate the enhancement in performance from using the SuperSpeed Golf™ clubs and recommended warm-up protocol. Therefore, the aims of this Thesis were to: (1) systematically review and quality appraise articles addressing golf and 3D biomechanics (Chapter One); (2) systematically review and quality appraise articles addressing weighted equipment used during warm-ups for ball striking sports (Chapter Two); (3) investigate the acute effects of using the SuperSpeed clubs and recommended warm-up protocol on golf driving performance and biomechanics (Chapter Three); and (4) investigate the persistence of the effects of the SuperSpeed warm-up protocol on clubhead, ball, and swing biomechanics during a simulated golf tournament scenario (Chapter Four).

As part of the systematic review in Chapter One, 23 articles on golf and 3D biomechanics in professional or high level amateurs (handicap < 5.0) were assessed for their methodological quality, with only two articles achieving a strong quality score based on the Effective Public Health Practice Project (EPHPP) quality assessment tool. From the reviewed studies, the biomechanical measures most consistently reported to relate to clubhead and ball speed were pelvis and torso axial rotation, pelvis and torso rotational velocity, X-factor, and X-factor stretch.

As part of the systematic review in Chapter Two, seven articles on weighted equipment used during warm-ups for ball striking sports were assessed for their methodological quality, with only one article achieving a strong quality score based on the EPHPP quality assessment tool. All articles meeting inclusion addressed the sport of baseball. From the reviewed studies, the use of weighted equipment as a means to enhance subsequent swing performance in baseball was either ineffective or detrimental. The lack of research in ball striking sports outside of baseball and the generally weak quality of articles in the area highlight the need for better quality studies in different ball striking sports. Based on the current systematic review findings, there is limited evidence to substantiate the use of weighted equipment in golf as means to enhance subsequent performance.

In Chapter Three, 12 (7 males, 5 females) high level amateurs (handicap < 3.0) completed a golf-specific control and weighted club (SuperSpeed Golf™) warm-up protocol followed by 5 swings using their own driver assessed using 3D motion analysis (500 Hz, Qualisys AB, Sweden). Swing, angular velocity, X-factor, and centre of mass (COM) parameters were extracted and compared between warm-up conditions using Cohen's standardised effect size (ES). The SuperSpeed warm-up protocol led to significant ($p < 0.05$) *small* (ES > 0.2) and likely (greater than 75% likelihood) changes in clubhead speed (2.6 mph faster), angular velocity of the torso (18.2 °/s faster) and lead arm (36.0 °/s faster), and COM position at the top of backswing in the x direction (0.59 cm closer to the target) and at impact in the y direction (0.34 cm more to the left of the target). However, no significant change was seen in ball speed, leading to a significant *moderate* and likely negative change in smash factor (-0.3 clubhead speed to ball speed ratio), suggesting that the increased clubhead speed was not efficiently transferred to the ball at impact.

In Chapter Four, the same 12 (7 males, 5 females) high level amateurs (handicap < 3.0) completed five sets of five swings walking 400 m between sets under the two randomised warm-up conditions (golf-specific control and SuperSpeed). The persistence of any meaningful effects detected in the initial set was assessed across sequential sets. The significant *small* and likely changes in clubhead speed, smash factor, angular velocity of the torso and lead arm, and two COM variables subsequent the SuperSpeed warm-up compared to the control warm-up in the initial set were no longer meaningful from the second set onward after walking the distance of a simulated golf hole. These findings suggest that the SuperSpeed warm-up protocol performed pre-tournament does not meaningfully improve golfing performance in a golf-specific context from the second hole onwards.

Results from the two systematic reviews highlight the need for better quality methodological studies in golf biomechanics and use of weighted implements in ball striking sports. From the golf biomechanics literature reviewed, pelvis and torso axial rotation, rotational velocity, X-factor, and X-factor stretch were identified as factors related to driving performance. Although the weighted equipment literature reviewed did not substantiate its use as part of warm-up for performance enhancement, the literature was limited to baseball, warranting further research specifically in golf. The two experimental studies compared the effects of using the SuperSpeed Golf™ weighted clubs and warm-up protocol versus a golf-specific control warm-up protocol in high level amateur golfers. Although SuperSpeed significantly and meaningfully increased clubhead speed and influenced a subset of swing biomechanics acutely, these changes were no longer meaningful after walking the distance of a simulated golf hole. The Royal and Ancient rules of golf prohibit the use of ergogenic aids like the SuperSpeed clubs once tournament play has started. Therefore, the financial, time, and practical value of investing in the SuperSpeed Golf™ weighted clubs product are questionable as might only improve performance on the first hole. Future research is needed to determine the influence of prior exposure to SuperSpeed Golf™ and of changing the sequence or weights of the clubs on the acute and persistence of potentiation effects. The current experimental studies were laboratory-based and involved high level amateurs; hence, generalisation to on-course environments and lesser or better-skilled golfers needs confirmation.

Acknowledgements

To begin, I would like to thank all my friends and family for their assistance and support through this Thesis. To my mother, father and sister thank you for encouraging me throughout this process. To Jay Carter, thank you for answering ever question I had that was golf or swing related. To Ivana, your knowledge, understanding and assistance was invaluable and thank you to the University of Waikato Adam Centre PhD students for keeping me sane. To all the volunteers that participated in my research thank you for giving your time and golfing skills to contribute to this Thesis.

To my primary supervisor, Dr Kim Hébert-Losier, your assistance, support and patience cannot be thanked enough. I would not have been able to navigate the ups and downs of this process if it was not for you. The knowledge, passion, and time you investment into assisting the development of students you supervise, including myself is second to none.

Finally, a big thank you to my best friend and partner Rachel Curle. Although you spent over three quarters of this process overseas, I have always felt that you were beside me. Your continued support with my learning and professional career is one of many values that have kept me advancing. I am looking forward to seeing what lies ahead for us.

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List of Abbreviations

ATP – Adenosine triphosphate

ASIS – Anterior superior iliac spine

$\text{Ball}_{\text{peak\_R}}$ – Peak resultant ball speed

$\text{Ball}_{\text{peak\_X}}$ – Peak anterior-posterior ball velocity

$\text{Ball}_{\text{peak\_Y}}$ – Peak medial-lateral ball velocity

$\text{Ball}_{\text{peak\_Z}}$ – Peak superior-inferior ball velocity

BBS – Baseball bat speed

BS – Ball speed

C – Celsius

Ca^{2+} – Calcium

CD – Carry distance

CH – Clubhead

CHS – Clubhead speed

$\text{CHS}_{\text{impact}}$ – Clubhead impact speed

CHS_{peak} – Clubhead peak speed during downswing

CL – Confidence limit

cm – Centimetre

cm/s – Centimetres per second

CMJ – Countermovement jump

COM – Centre of mass

C7 – Cervical vertebrae seven

Dom – Dominant side

DS – Downswing

EPHPP – Effective Public Health Practice Project

ES – Effect size

g – Grams

GLW – George Leslie Wardell

HBS – High ball speed

HW – Heavier than standard bat mass

HREC – Human research ethics committee

Hz – Hertz

h/week – Hours per week

IH – Ivana Hanzlíková

KHL – Kim Hébert-Losier

kg – Kilograms

km – Kilometre

LED – Light-emitting diode

LL – Lower confidence limit

LPGA – Ladies Professional Golfers Association

LW – Lighter than standard bat mass

L&R – Left and right

L4 – Lumbar vertebrae four

m – Meter

MA – Motion Analysis

MBI – Magnitude-based inference

mm – Millimetre

mph – Miles per hour

ms – Milliseconds

m/s – Meters per second

N – No

n – Counts

ND – Non-dominant side

NS – Not specified

n/a – Not applicable

p – p-value

PAP – Post-activation potentiation

PCr – Phosphocreatine

PGA – Professional Golfers Association

PPT – Peak Performance Technologies

PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-Analyses

PSIS – Posterior superior iliac spine

R – Right

RLC – Regulatory light chains

s – Seconds

SD – Standard deviation

SSC – Stretch shortening cycle

SW – Standard weight

TD – Total distance

™ – Trademark

ToB – Top of backswing

T10 – Thoracic vertebrae ten

UL – Upper confidence limit

y – Years

α – Alpha

β – Beta

§ – Likelihood > 75%.

? – Cannot tell

° – Degrees

* – p-value < 0.05

~ – Followed by

1RM – One repetition maximum

3D – Three dimensional

3RM – Three repetition maximum

Thesis Overview

The main aim of this Thesis was to investigate the acute and persistence of potentiation effects of a weighted equipment (SuperSpeed Golf™) warm-up on golf driving performance. The Thesis is comprised of five chapters (**Figure 1**), with each chapter formatted as an individual article suitable for submission to a peer-reviewed journal. Due to the nature of the Thesis with publication format, some of the information may be repeated between chapters and throughout the Thesis. Chapter One and Chapter Two are systematic reviews of the literature, with existing literature assessed for methodological quality using the Effective Public Health Practice Project quality assessment tool. Chapter Three and Chapter Four are experimental studies that examine the potentiating effects of the SuperSpeed Golf™ warm-up protocol compared to a control golf-specific warm-up protocol on subsequent golf driving performance and biomechanics acutely and across sets, respectively. The final chapter (Chapter Five) summarises the key findings from the two systematic reviews and two experimental studies included in this Thesis, and highlights the strengths, limitations, practical implications, and direction for future research.

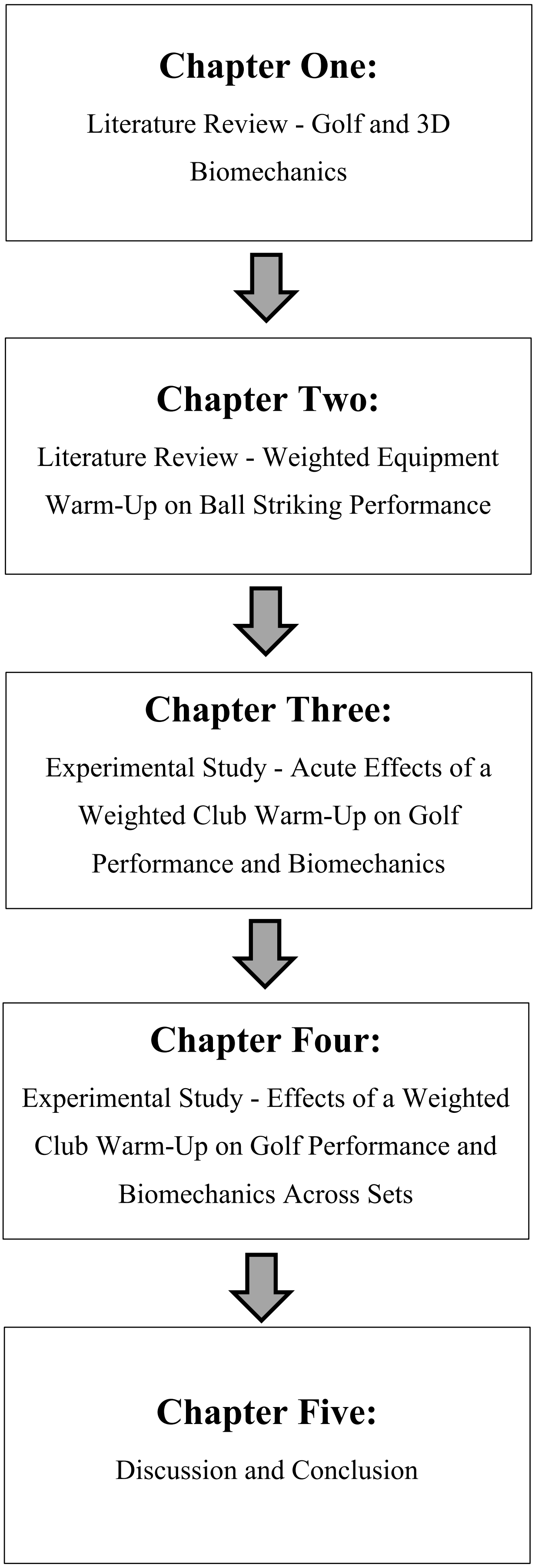

Figure 1. Flow diagram of Thesis structure.

Chapter One: Literature Review – Golf and 3D Biomechanics

Abstract

Introduction:

The golf swing is a very complex movement requiring control of multiple degrees of freedom with the biomechanical measures linked with performance varying across skill levels. This systematic review aimed to identify the biomechanical measures related to clubhead and ball speed of the long game in high level amateur or professional golfers.

Methods:

The Pubmed, Scopus, and Web of Science electronic databases were searched on the 3rd December 2018 using the search syntax "Golf AND Biomechanics". Only original research using 3D data collection methods, involving golfers with a handicap < 5.0, and reporting clubhead or ball speed metrics were included. The methodological quality of articles was assessed using a modified version of the Effective Public Health Practice Project (EPHPP) tool.

Results:

The systematic review included 23 studies assessing 140 professional and 311 high level amateur golfers predominantly male (81%) using 3D motion capture (50 – 500 Hz). Methodological quality was mostly weak (48%) or moderate (43%). The weighted means of clubhead and ball speed were 106.7 ± 3.1 and 154.5 ± 6.6 mph for males, and 89.8 ± 0.9 and 127.0 ± 1.5 mph for females, respectively. The biomechanical measures most consistently reported to relate to clubhead and ball speed were X-factor, X-factor stretch, as well as pelvis and torso axial rotation and rotational velocity.

Conclusion:

Published research has identified a subset of biomechanical measures associated with clubhead and ball speed in professional and high level amateurs, although the strength of association varied between studies. Future research in the area needs to be of stronger methodological quality, conducted in ecologically valid environments to enhance our understanding of the biomechanical variables associated with clubhead and ball speed.

Introduction

The game of golf requires extensive biomechanical control of the human body in space with the aim to strike a ball with a club as precisely as possible towards a target. The number of individuals who participate in golf is considerably high, with an estimated one hundred thousand New Zealanders and one million Australians partaking in the sport each year[1,2]. Golf participants are diverse in terms of age, ethnicity, and socio-economic groups, as well as skill level. Most golfers play for recreation; however, there is a subset of players who are professionals and generate income from the sport. The potential for large financial gains at the professional level continuously drive players to enhance their level of performance. For instance, the 2018 top-earner of the Professional Golfers Association (PGA) list made more than eight million American dollars[3], with Tiger Wood's career earnings exceeding 118 million American dollars[3]. To assist in better understanding and improving golfing performance, a growing number of studies are examining the biomechanical demands of golf and the metrics that relate to golf swing performance.

1.1 Golf performance measures

The game of golf consists of a combined score of a player's strokes over 18 holes that is related to the par of the golf course and compared to scores from other players[4]. The best performance is dictated by the least number of golf strokes over the duration of the event[5]. Previous research and review articles have used different variables to quantify golfing performance over the course of a season[6-9], making cross study comparisons challenging. These variables include total season earnings, top five or ten finishes, and world ranking points[6-9]. These measures largely reflect a player's performance compared to others[4]. Season earnings and ranking points are measures that depend on additional external factors outside of on-course golf performance. The purse of an event or ranking points awarded depend on sponsorships and the calibre of the playing field. Thus, factors outside of a player's control can influence these performance metrics. In addition, season earnings and ranking points can make the comparison between amateurs and professionals difficult. While the use of top finishes is a direct comparison of a player's performance in relation to the playing field, it does not consider players actual golfing performance and golf course played.

Scoring average is the performance measure of a player's average score against the golf course throughout the duration of a season. Environmental factors largely influence the performance of a golfer given that the sport is played outdoors. Course maintenance, weather conditions, and temperature can hinder the ability of players to achieve a low stroke count[10-13]. Environmental influences create a flaw within the scoring average, as competitors are playing at different times during the day and year[4]. For example, large professional and amateur fields have split starting times (tee times), resulting in morning and afternoon sessions with potentially different playing conditions. Additionally, the golf course players compete on throughout the year have varying levels of difficulty. To minimise the influence of environmental factors and enable a more accurate comparison of performance between players, a weighted score average metric was developed that compares a player's score in relation to the scoring average of the players competing on that day[8]. Therefore, the weighted scoring average provides a better representation of a golfers playing ability relative to others and has a stronger correlation to season earnings than the scoring average[8,9].

1.2 Partial shots

The game of golf can be divided into three main tasks (or partial shots): the long game, the short game, and putting. The objective of the long game is to decrease the amount of approach shots or approach length left to the putting surface; hence, the long game relies notably on power and distance[14,15].The short game requires direction, distance, and accuracy of shots within close proximity, typically less than 91.44 meters or 100 yards[14]. The task of putting requires precision and control of shots over a short distance to 'sink' the ball in the hole[16]. Advances in technology has allowed gathering of statistical information on each of these three main tasks. All three tasks influence performance measures (weighted scoring average) to various extents[5,6,14,15]. Prior to the year 2000, the strongest correlations to scoring average and earnings were linked with putting and short game performances[4,6,8,14]. With enhancements in technology and focus on physical preparation of athletes, the game of golf in more recent years exhibits a stronger correlation with long game performance[6,12,14,15,17-20]. PGA Tour data between 2003 and 2010, comprising of over eight million golf shots, illustrate that the long game contributes to over two-thirds of the difference in scores between PGA Tour competitors[14]. Given the importance of the long game in tour performance and earnings, professional golfers and coaches place a lot of effort and time in increasing driving performance. The ability to generate high clubhead speeds has previously been shown to correlate to increases in a player's performance (scoring)[19]. Increasing driving distance off the tee decreases the distance to the green, which ultimately results in better approach-shot accuracy[15,20,21] and likelihood of low stroke count.

1.3 Biomechanics of golf

The golf swing is a very complex movement, requiring control of multiple degrees of freedom of joints in space[22-25]. Players, coaches, and researchers are more commonly using biomechanical tools to assist in training, monitoring, understanding, and improving the golf swing at a group and individual level[16,26]. The use of sophisticated biomechanical tools allows for the precise quantification and further understanding of the complexities surrounding the kinetic and kinematic characteristics of the golf swing[16]. A range of technologies have been used for this purpose, including electromagnetic[27,28] and camera-based[27,29,30] systems. Optoelectronic three dimensional (3D) biomechanics technology is the gold-standard method for quantifying human movement non-invasively[27] and can provide a detailed analysis of the multifaceted movement of golf using retro-reflective markers and infrared camera-based technology with high capture rates[11,12]. Researchers have used 3D biomechanics in an attempt to characterise the 'ideal' golf swing, with the overall aim of improving performance and reducing the risk and severity of golf-related injuries[16].

1.4 Biomechanics of the long game

The golf swing can be divided into three main phases: backswing, downswing, and follow-through. The backswing initiates as the club and body starts to rotate away from the target, with the purpose of this phase being to stretch the main muscles and joints (such as the torso and pelvis) involved during the downswing[31]. The downswing relies on the kinetic chain principle, which is the transfer of energy and momentum through sequential body segments to achieve the greatest magnitude in the most distal segment[32,33]. In golf, the energy transfers from the proximal body segments towards the distal body segments to accelerate the clubhead (i.e., the most distal segment of the kinetic chain) to reach a maximal velocity at impact with the golf ball[32]. The follow-through phase commences after impact with the golf ball, and has the purpose of decelerating the body and clubhead to a final stationary position. Although the three phases are inter-related, biomechanical studies in golf indicate that the downswing phase influences golf performance measures the most, more so than the backswing and follow-through phases[17,34-36].

The downswing phase involves the generation of high clubhead speeds capable of exceeding 49.2 m/s or 110 miles per hour (mph)[29,30,36-40]. Analysis of the downswing movement pattern using 3D biomechanics allows for differences between professional, high level amateur (handicap < 5.0), and amateur (handicap > 5.0) golf players to be quantified and analysed[35,41-45]. At the top of the backswing, professionals are able to create a larger range of rotation in the torso and shoulders[35,41], as well as increased amounts of rotational separation between the torso and pelvis (X-factor) at the top of the backswing, during downswing, and at impact[35,41,42,44]. Additionally the radial deviation of the wrist during the downswing and at impact also differs between skill-level groups[45]. Studies indicate that players within these groups, particularly the low-skilled amateurs, adopt different techniques at ball impact to compensate for suboptimal backswing and downswing mechanics[34,41,42,45,46]. A correlation is also seen between skill level and clubhead speed, with PGA professional golfers producing increased clubhead speeds than lesser-skilled players[39,40,47] and clubhead speeds strongly related to scoring average and handicap levels[19,48].

With skill level influencing golfing technique and biomechanics, it becomes imperative for coaches and athletes to focus on understanding and developing biomechanical traits associated with performance. With two thirds of golfing performance (based on weighted scoring average) coming from the long game[14], particular attention should be given to the biomechanics of this golfing task. Hence, the aims of this systematic review of the literature was to critically appraise and summarise the research on the biomechanical metrics related to golf performance of the long game at a high level amateur or professional (handicap < 5.0) level. Of particular interest was the studies that used 3D motion analysis to investigate golf driving performance.

Methods

2.1 Systematic search

This systematic review followed the structure and reporting requirements of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement[49]. The Pubmed, Scopus, and Web of Science electronic databases were systematically searched on the 3rd of December 2018 using the search syntax "Golf AND Biomechanics". Given that camera-based and electromagnetic-based systems should not be used interchangeably[27] and that the experimental studies planned for this Thesis were relying on camera-based 3D systems, articles needed to meet the following inclusion criteria:

1. Use 3D data collection methods with infrared motion capture technology.
2. Have performance-driven aims.
3. Involve participants with a skill level equal to that of a professional or high level amateur (handicap < 5.0).
4. Examine golfers with no current musculoskeletal injuries.
5. Be an original research article published in a peer-reviewed journal.
6. Be available in the English language.

One reviewer (GLW) conducted the three database searches and collected all articles in a reference manager software (Endnote, version X9, Clarivate Analytics, Philadelphia, PA, USA). Duplicate articles from the database searches were removed before inclusion and exclusion criteria were used to screen the titles, abstracts, and full-text articles in that order. A second independent reviewer (KHL) verified the results from the screening process. No additional articles were added through supplementary searches of reference lists of included articles, publications of key authors in the field, or additional database searches (Google Scholar and SPORTDiscus). The search strategy and article selection process are illustrated in **Figure 2**.

2.2 Quality assessment

A modified version of the Effective Public Health Practice Project (EPHPP) checklist was used to quality assess the articles meeting inclusion given that no specific quality assessment tool has been designed for sport science. The 14-item EPHPP quality assessment tool was chosen for this review given that it suited the study design of articles meeting inclusion[50,51], has demonstrated reliability[50,51], and has been used in review of sport science literature previously[52]. The standardised template of the EPHPP score sheet was adapted to incorporate additional study design methods (cross sectional in section B) and confounders of importance specific to this review (sex, skill level, and age in section C). An additional grade of "missing data" was also added to the withdrawals and drop outs in section F. If the study design did not incorporate an intervention, a grade of "Fair" was allocated to blinding of the outcome assessors in section D.

Two reviewers (GLW and IH) met before independently quality assessing the articles to agree on how to score each item based on the EPHPP checklist manual. After independent assessment, the two reviewers met to discuss disagreements and achieve a consensus rating. A third reviewer (KHL) was identified to resolve any differences in opinion, but was not required. The final quality assessment score was calculated as recommended by the EPHPP scoring guidelines. A study was allocated an overall quality rating of "strong" if none of the major components were rated as weak, "moderate" if only one major component was rated as weak, or "weak" if two or more of the components were rated as weak.

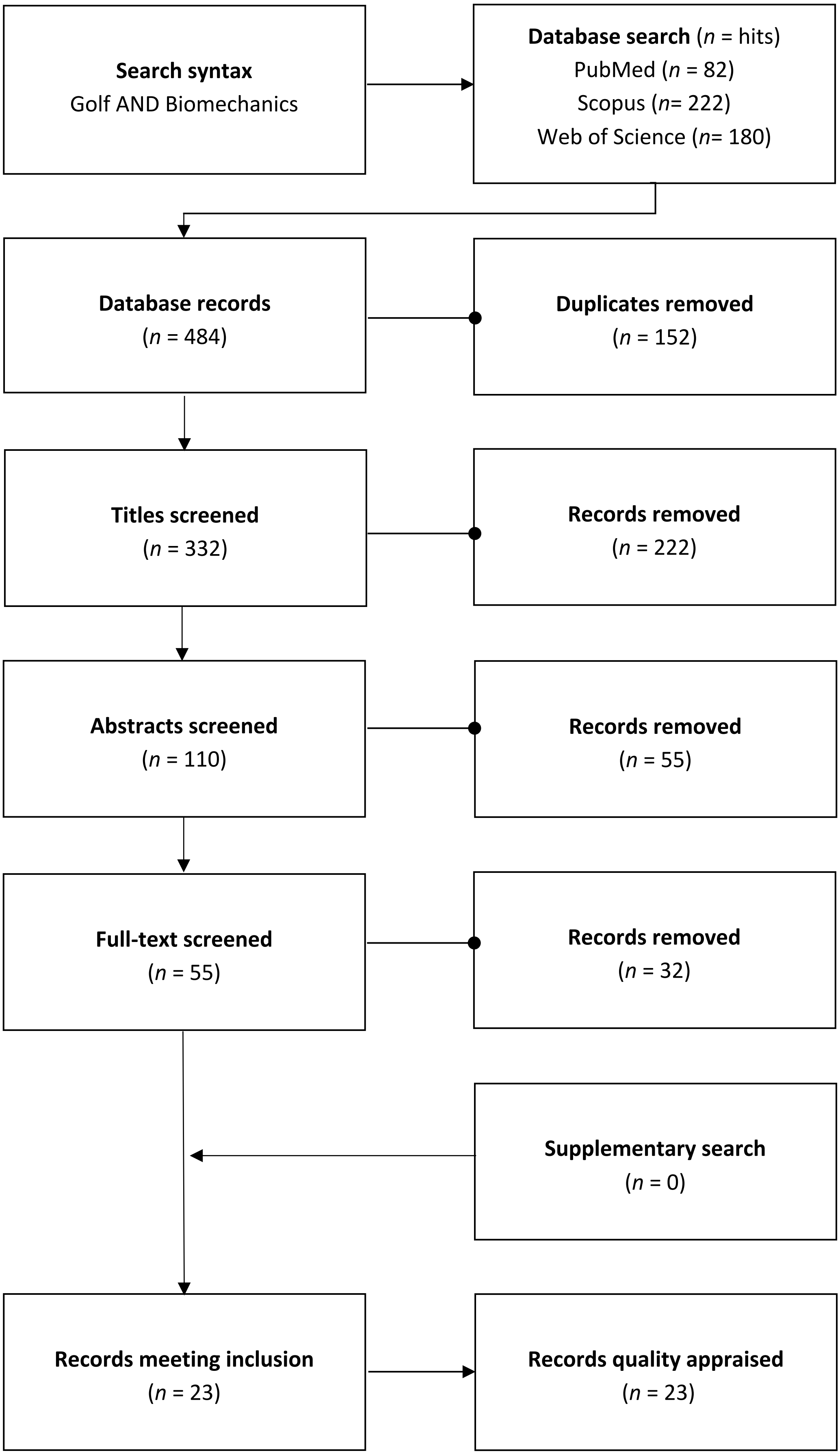

Figure 2. Flow diagram of the article selection process.

2.3 Data extraction

Information concerning study aims; participants; 3D methods; capture rate; marker model; experimental protocol, including warm-up methods; swing, body, and performance measures; and key findings were extracted from each article using a standardised format by one reviewer (GLW). Completeness of data extraction was verified by a second reviewer (KHL).

2.4 Data analysis

Data extracted were managed and analysed using Microsoft Excel 2016 (Microsoft Corporation, Redmont, WA, USA). Descriptive statistics for the data were expressed using means and standard deviations (mean ± SD), ranges (minimum to maximum), counts (*n*), or percentages (%) depending on the data type. When appropriate, weighted means based on sample sizes were calculated for height, mass, and age of participants, as well as performance measures for both clubhead and ball speed.

2.5 Participant characteristics

"Professional" was defined as having an affiliation to the PGA, Ladies Professional Golfing Association (LPGA), or other professional playing associations. "High level amateur" was defined as amateurs of a high skill level (handicap ≤ 5.0). "Amateur" was defined as amateurs of moderate to low skill level (handicap > 5.0).

Results

3.1 Quality assessment

The quality scores from the modified EPHPP checklist are presented in **Table 1** for the 23 studies meeting inclusion. The methodological quality was strong in two studies[29,53], moderate in ten studies[34,37,38,42,45,54-58], and weak in the remaining eleven[17,30,35,36,41,43,44,46,59-61].

Table 1. Effective Public Health Practice Project quality appraisal score for each of the assessed golf and 3D biomechanics articles (*n* = 23).

Article	**Representative of Study population**	**% of participants agreed to partake**	**Study Design**	**Difference between groups prior**	**% of relevant confounders controlled**
Beak et al. [54]	Somewhat likely	?	Cross sectional	N	> 80%
Brown et al. [17]	?	?	Cross sectional	N	> 80%
Choi et al. [55]	Somewhat likely	?	Cross sectional	N	> 80%
Egret et al. [59]	?	?	Cross sectional	N	> 80%
Fedorcik et al. [45]	Somewhat likely	?	Cohort 2	N	> 80%
Ferdinands et al. [46]	?	?	Cross sectional	Y	< 60%
Healy et al. [34]	Somewhat likely	?	Cohort 2	N	60 – 79%
Horan et al. [60]	Not likely	?	Cohort 2	N	> 80%
Horan et al. [61]	Not likely	?	Cohort 2	N	60 – 79%
Horan et al. [36]	Not likely	?	Cross sectional	N	60 – 79%
Joyce [29]	Somewhat likely	60 – 79%	Cross sectional	N	60 – 79%
Joyce [53]	Somewhat likely	?	Cross sectional	N	> 80%
Joyce et al.[37]	Not likely	60 – 79%	Cross sectional	N	> 80%
Joyce et al.[58]	Somewhat likely	?	Cross sectional	N	> 80%
Joyce et al. [56]	?	?	Cross sectional	N	60 – 79%
Kwon et al. [38]	Somewhat likely	?	Cross sectional	N	> 80%
McNally et al. [43]	?	?	Cross sectional	N	60 – 79%
Meister et al. [44]	Not likely	< 60%	Cross sectional	N	> 80%
Myers et al. [35]	?	?	Cross sectional	N	60 – 79%
Sorbie et al. [30]	?	?	Cohort 1	N	> 80%
Steele et al. [42]	Somewhat likely	?	Cohort 2	N	60 – 79%
Zheng et al. [57]	Somewhat likely	?	Cohort 2	N	60 – 79%
Zheng et al. [41]	?	?	Cohort 2	N	60 – 79%

Notes. Cohort 1, Cohort study design, one group pre and post; Cohort 2, Cohort study design, two groups pre and post; N, No; Y, Yes; ?, Cannot tell.

Article	Assessors aware of intervention	Participants aware of research question	Valid	Reliable	Drop-outs reported	% participants completion	Score
Beak et al. [54]	n/a	?	?	?	N	> 80%	Moderate
Brown et al. [17]	n/a	?	?	?	N	> 80%	Weak
Choi et al. [55]	n/a	?	?	?	N	> 80%	Moderate
Egret et al. [59]	n/a	?	?	?	N	> 80%	Weak
Fedorcik et al. [45]	n/a	?	?	?	N	?	Moderate
Ferdinands et al. [46]	n/a	?	?	?	N	?	Weak
Healy et al. [34]	n/a	?	?	?	N	> 80%	Moderate
Horan et al. [60]	n/a	?	?	?	N	> 80%	Weak
Horan et al. [61]	n/a	?	?	?	N	> 80%	Weak
Horan et al. [36]	n/a	?	?	?	N	?	Weak
Joyce [29]	n/a	?	Y	?	Y	60 – 79%	Strong
Joyce [53]	n/a	?	Y	?	Y	60 – 79%	Strong
Joyce et al.[37]	n/a	?	Y	Y	N	> 80%	Moderate
Joyce et al.[58]	n/a	?	?	?	Y	?	Moderate
Joyce et al. [56]	n/a	?	Y	?	Y	> 80%	Moderate
Kwon et al. [38]	n/a	?	N	?	N	> 80%	Moderate
McNally et al. [43]	n/a	?	N	N	N	> 80%	Weak
Meister et al. [44]	n/a	?	?	?	N	> 80%	Weak
Myers et al. [35]	n/a	?	?	?	N	> 80%	Weak
Sorbie et al. [30]	?	?	Y	?	N	?	Weak
Steele et al. [42]	n/a	?	?	?	N	?	Moderate
Zheng et al. [57]	n/a	?	?	?	N	> 80%	Moderate
Zheng et al. [41]	n/a	?	?	?	N	> 80%	Weak

Notes. N, No; n/a, Not applicable; Y, Yes; ?, Cannot tell.

3.2 Study characteristics

Within the 23 articles appraised, 15 studies[17,29,35-38,43,44,46,53-56,58,59] implemented a cross sectional study design, seven[34,41,42,45,57,60,61] implemented a cohort 2 study design (two groups pre and post), and one study[30] used a cohort 1 study design (one group pre and post). Golfing performance was based on golf ball and/or clubhead speed (**Table 2**). Clubhead speed was reported in 20 studies[17,29,30,34-38,42-44,46,53-56,58-61], while golf ball speed was reported in 8 studies[17,34-37,42,46,58,61]. Thirteen studies[17,29,30,35-38,53-56,58,61] aimed to investigate the potential influence of torso and pelvis biomechanical factors on golfing performance.

3.3 Participant characteristics

In total, 643 healthy participants were included across the 23 studies, with an average sample size of 28 ± 22 (range: 5 to 100). Within the 643 participants, 459 were male, 79 were female, and the sex of the remaining 105 was not specified. A range of skill levels were represented; however, only the data recorded for high level amateur (handicap $\leq$ 5.0, 311 participants) or professional (140 participants) golfers were considered. High level amateur and professional golfers comprised a total of 48% and 22% of the participants included in the reviewed studies. The male participants from the high level amateur to professional skill levels were 1.81 ± 0.02 m tall, 82.05 ± 3.91 kg in body mass, and 28.55 ± 4.57 years old, whereas the females were 1.68 ± 0.01 m tall, 63.08 ± 1.46 kg in body mass, and 27.17 ± 3.31 years old. The weighted means for clubhead and ball speed for high level amateur and professional skill level participants were calculated, with males having a reported clubhead and ball speed of 106.7 ± 3.1 mph or 47.7 ± 1.4 m/s and 154.5 ± 6.6 mph or 69.1 ± 3.0 m/s, and females of 89.8 ± 0.9 mph or 40.1 ± 0.4 m/s and 127.0 ± 1.5 mph or 56.8 ± 0.7 m/s, respectively. Additional key characteristics of studies are presented in **Table 2**.

Table 2. Characteristics of studies in golf and 3D biomechanics ($n = 23$)

Author (Quality)[a]	**3D system and sampling rate**	**Marker set**	**Participants**	**Swing variables**	**Body variables**
Beak et al. [54] (Moderate)	6 VICON cameras 120 Hz	9 markers; 4 pelvis, 4 torso, 1 club head.	14 males; Skill level: Professional; Height: 176 ± 7.9 m; Mass: 74.6 ± 9.3 kg; Age: 29 ± 8 y	CHS and DS time	Pelvis and torso
Brown et al. [17] (Weak)	12 MA cameras 240 Hz	40 markers; C7, T10, L4, suprasternal notch, and L&R acromion processes, ASIS, PSIS, upper and lower limbs, and reflective tape at base of grip and hosel of club.	16 females; Skill level: Amateur < 5; Height: 1.68 ± 0.06 m Mass: 65.94 ± 6.23 kg; Age: 24.8 ± 7.3 y	CHS, BS, launch angle and spin rate	Pelvis and torso X-factor
Choi et al. [55] (Moderate)	6 VICON cameras 120 Hz	14 markers; C7, T10, suprasternal notch, xiphiod process, and L&R ASIS & PSIS, femoral epicondyle, thigh surface, and CH, shaft and golf ball.	21 males; Skill level: Professional; Height: 1.775 ± 0.87 m Mass: 79.2 ± 10.0 kg; Age: 31 ± 6 y	CHS and DS time	Hip rotation, pelvis and torso
Egret et al. [59] (Weak)	5 VICON cameras 50 Hz	14 markers; L&R acromioclavicular joint, elbow epicondyle, apophysis styloid radius, ASIS, knee lateral condyles, and lateral malleoli.	7 males; Skill level: Amateur 0.4 ± 1.1; Age: 17 to 34 y	CHS	Hip rotation, shoulder rotation, knee flexion, and stance width
Fedorcik et al. [45] (Moderate)	8 MA cameras 240 Hz	? markers; L&R radial and ulnar styloid process, and base of the 3rd metacarpal.	28 males; Skill level: Amateur < 5 ($n = 15$); Height: 1.81 ± 0.04 m Mass: 79.83 ± 12.87 kg Age: 23.8 ± 5.17 y		Bilateral wrist flexion/extension, and radial/ulnar deviation
Ferdinands et al. [46] (Weak)	8 Falcon cameras 240 Hz	55 marker; C7, mid-PSIS, suprasternal notch, xiphoid process, crown, forehead, quarter shaft, mid shaft, club hosel, club toe, club head top, golf ball and L&R forefoot, toe-shoe, heel, lateral and medial ankle, mid shank, lateral and medial knee, ASIS, great trochanter, mid-back, acromion, high triceps, lateral bicep, anterior and posterior deltoid, medial and lateral elbow, medial and lateral wrist, 3rd metacarpal.	5 participants; Skill level: Amateur handicap < 2.0; Age: 26.6 ± 4.8 y	CHS, BS, and Club path	Pelvis, torso, shoulders, arm, forearm, hand, X-factor, X-factor stretch

Author (Quality)[a]	**3D system and sampling rate**	**Marker set**	**Participants**	**Swing variables**	**Body variables**
Healy et al. [34] (Moderate)	12 VICON cameras 250 Hz	45 markers; C7, T10 suprasternal notch, xiphoid process, R scapular crown, and L&R temple, acromioclavicular joint, bicep, epicondyle of the elbow, forearm, lateral and medial wrist, 2nd metacarpal, ASIS, PSIS, thigh, epicondyle of the knee, shank, lateral malleolus, calcaneus, and 2nd and 5th metatarsal heads. Three shaft markers, and one marker placed at the end of a solid metal bar attached to the club.	40 males; Skill level: Amateur (HBS: *n* = 15); Height: 1.799 ± 0.052 m; Mass: 78.8 ± 7.19 kg; Age: 27.5 ± 10 y.	CHS, BS, club face angle, tempo, club rotation and impact point	Shoulder, elbow, hip rotation, pelvis, knee, X-factor, and X-factor stretch
Horan et al. [60] (Weak)	? VICON cameras 500 Hz	11 markers; C7, T10, suprasternal notch, xiphoid process, and L&R ASIS, PSIS, heel, and CH	19 males & 19 females; Skill level: Professional & Amateur handicap < 4.0; Males Height: 1.80 ± 0.05 m Mass: 80.2 ± 9.1 kg Age: 26 ± 7 y; Females: Height: 1.67 ± 0.06 m Mass: 62.2 ± 9.6 kg Age: 25 ± 7 y	CHS	Pelvis and torso
Horan et al. [61] (Weak)	8 VICON cameras 500 Hz	12 markers; C7, T10, suprasternal notch, xiphoid process, L&R heel, ASIS, PSIS, and CH. Golf ball covered with reflective tape.	19 males & 19 females; Skill level: Professional & Amateur handicap < 4.0; Males Height: 1.80 ± 0.05 m Mass: 80.2 ± 9.1 kg Age: 26 ± 7 y; Females: Height: 1.67 ± 0.06 m Mass: 62.2 ± 9.6 kg Age: 25 ± 7 y	CHS and BS	Pelvis and torso
Horan et al. [36] (Weak)	8 VICON cameras 500 Hz	16 markers; C7, T10, suprasternal notch, xiphoid process, L&R heel, ASIS, PSIS, occipital protuberance, frontal eminence, and CH. Golf ball covered with reflective tape.	14 males; Skill level: Professionals; Height: 1.79 ± 0.04 m Mass: 81.2 ± 9.6 kg Age: 27 ± 8 y	CHS and BS	Pelvis, torso and head
Joyce [29] (Strong)	10 VICON cameras 250 Hz	A previously validated multi-segment trunk model (Joyce et al., 2010). 12 markers; T10, L1, xiphoid process, suprasternal notch, and L&R acromion process, ASIS, PSIS, and 2 shaft markers.	15 males; Skill level: Amateur handicap 2.5 ± 1.9; Age: 22.7 ± 4.3 y	CHS	X-factor and X-factor stretch

Author (Quality)[a]	**3D system and sampling rate**	**Marker set**	**Participants**	**Swing variables**	**Body variables**
Joyce [53] (Strong)	10 VICON cameras 250 Hz	A previously validated multi-segment trunk model (Joyce et al., 2010). 12 markers; T10, L1, xiphoid process, suprasternal notch, and L&R acromion process, ASIS, PSIS and 2 shaft markers.	15 males; Skill level: Amateur handicap 2.5 ± 1.9; Age: 22.7 ± 4.3 y	CHS	Torso
Joyce et al.[37] (Moderate)	10 VICON cameras 250 Hz	Previously validated model[62]. 12 markers; T10, L1, xiphoid process, suprasternal notch, and L&R acromion process, ASIS, PSIS and 2 shaft markers.	15 males; Skill level: Amateur handicap 2.5 ± 1.9; Height: 1.80 ± 0.10 m Mass: 72.9 ± 12.2 kg; Age: 22.7 ± 4.3 y	CHS and BS	Pelvis and torso
Joyce et al.[58] (Moderate)	10 VICON cameras 500 Hz	Combination of previously validated models[62-64] Left arm for right hand golfer model were also used. 21 markers; T10, L1, xiphoid process, suprasternal notch, and L&R acromion process, ASIS, PSIS, arm, wrist and 2 shaft markers.	20 males; Skill level: Amateur handicap 1.9 ± 1.9; Age: 24.6 ± 5.6 y	CHS, BS, attack angle and launch angle.	Torso and wrist
Joyce et al. [56] (Moderate)	10 VICON cameras 500 Hz	A previously validated multi-segment model[62]. 12 markers; T10, L1, xiphoid process, suprasternal notch, and L&R acromion process, ASIS, PSIS and 2 shaft markers.	35 males; Skill level: Amateur handicap 5.0 ± 1.9; Age: 23.8 +/- 2.1 y	CHS, BS and Launch angle	Torso
Kwon et al. [38] (Moderate)	10 VICON cameras 250 Hz	65 markers; TWUGolfer marker set[65]	18 males; Skill level: Amateur handicap -0.6 ± 2.1; Height: 1.806 ± 0.055 m Mass: 82.6 ± 10.5 kg; Age: 31.7 ± 10.4 y	CHS	Pelvis, torso, head, shoulder, shanks, feet, upper arms, forearm, wrist, and hand
McNally et al. [43] (Weak)	8 VICON cameras 300 Hz	41 markers; C7, T10, R scapular, and L&R 2nd and 5th metatarsal heads, posterior calcaneus, medial and lateral malleolus, lateral mid-shank, medial and lateral knee joint line, lateral mid-thigh, ASIS, PSIS, acromion process, lateral mid-upper arm, medial and lateral epicondyle of the elbow, mid-forearm, medial and lateral wrist, and 2nd metacarpal joint.	36 males; Skill level: Professionals (n = 2) Amateurs handicap < 0.0 (n = 6); Mass: 87.0 ± 12.8 kg; Age: 36.3 ± 17.3 y	CHS	Pelvis, knee, and ankle

Author (Quality)[a]	**3D system and sampling rate**	**Marker set**	**Participants**	**Swing variables**	**Body variables**
Meister et al. [44] (Weak)	8 MA cameras 240 Hz	42 markers; Combination of Helen Hayes marker set, and an upper body marker set[66,67]. Three club markers and plastic golf bar covered in reflective tape.	15 males; Skill level: Professional (*n* = 10) ; Height: 1.83 ± 0.07 m Mass: 85.9 ± 11.5 kg; Age: 31.0 ± 5.9 y	CHS	Pelvis, torso, and X-factor.
Myers et al. [35] (Weak)	8 PPT cameras 200 Hz	13 markers; C7 and L&R Sacrum, ASIS, PSIS, acromion and lateral epicondyle of the humerus. Two club markers.	100 participants; Skill level: Amateur (HBS: *n* = 14) handicap 1.8 ± 3.2; Height: 1.82 ± 0.05 m Mass: 87.4 ± 13.4 kg; Age: 33.1 ± 11.4 y.	CHS, BS, launch angle, spin rates, CD, and TD.	Pelvis, torso, X-factor, and X-factor stretch
Sorbie et al. [30] (Weak)	8 VICON cameras 250 Hz	Vicon Plug-in-Gait Model, adapted to incorporate additional marker on the L4.	15 males; Skill level: Amateur handicap 3.3 ± 1.7; Height: 1.86 ± 0.05 m Mass: 80.9 ± 6.9 kg; Age: 23.8 ± 2.9 y	CHS, BS and CD	Pelvis, torso, X-factor and X-factor stretch
Steele et al. [42] (Moderate)	8 MA cameras 240 Hz	6 markers; L&R ASIS, acromion process, distal end of shaft. Plastic ball covered in reflective tape.	16 males; Skill level: Professional (n = 11); Height: 1.83 ± 0.07 m Mass 85.9 ± 11.5 kg; Age: 31.0 ± 5.9 y	CHS	Pelvis, torso, and X-factor
Zheng et al. [57] (Moderate)	6 MA cameras 240 Hz	Left radiocarpal joint, top and bottom of the club shaft, and L&R acromion process, lateral humeral epicondyle, greater trochanter, lateral femoral epicondyle, and lateral malleolus. Reflective tape on the shoe at the distal end of the mid toe. Golf ball covered in reflective tape.	25 males & 25 females; Skill level: Professional ; Male:_Height 1.834 ± 0.05 m Mass: 84.4 ± 8.8 kg; Age: 32 ± 5 y. Female: Height: 1.686 ± 0.05 m Mass: 62.6 ± 6.4 kg; Age: 32 ± 6.8 y		Pelvis torso, shoulder, elbow, forearm, and wrist
Zheng et al. [41] (Weak)	6 MA cameras 240 Hz	Left radiocarpal joint, top and bottom of the club shaft, and L&R acromion process, lateral humeral epicondyle, greater trochanter, lateral femoral epicondyle, and lateral malleolus. Reflective tape was also place on the shoe at the distal end mid toe and golf ball.	72 males; Skill level: Professional (*n* = 18); Height: 1.831 ± 0.048 m Mass: 83.7 ± 8.4 kg; Age: 31.6 ± 5.4 y		Pelvis torso, shoulder, elbow, forearm, and wrist

Notes. [a], Effective Public Health Practice Project quality assessment score; ASIS, Anterior superior iliac spine; BS, Ball speed; CD, Carry distance; CH, Clubhead; CHS, Clubhead speed; DS, Downswing; HBS, High ball speed; L&R, Left and right; MA, Motion Analysis; PPT, Peak Performance Technologies; PSIS, Posterior superior iliac spine; R, Right; TD, Total distance; ToB, Top of backswing; ?, Cannot tell

Table 2 *(continued)*. Characteristics of studies in golf and 3D biomechanics ($n = 23$)

Author (Quality)[a]	**Trials analysed**	**Warm-up protocol**	**Experimental protocol**	**Outcome measures and results**
Beak et al. [54] (Moderate)	3 randomly chosen trials out of 5 trials.	Static and dynamic stretching ~ practice trials	Warm up ~ 5 trials	High coupling strength between pelvis and upper torso coupling $r = 0.86$
Brown et al. [17] (Weak)	3 trials with highest CHS and BS out of 5 trials.	Practice trials	Warm up ~ Static calibration ~ 10 trials with a driver	Strong positive correlation between left hand grip strength and CHS ($r = 0.54$, $p < 0.05$). Negative correlation between handicap and CHS ($r = -0.612$, $p < 0.05$). Positive correlation between sitting flexibility test clockwise: ($r = 0.522$, $p < 0.05$); and counter clockwise ($r = 0.711$, $p < 0.01$).
Choi et al. [55] (Moderate)	Average of 3 trials with the best reconstructed 3D data quality out of 6 trials.	Self-directed	Warm up ~ Static calibration ~ 6 participant approved trials with their own driver	Lead hip and trunk coupling are significantly ($r < -0.5$, $p < 0.05$) related to CHS.
Egret et al. [59] (Weak)	All 6 trials with each club.	Practice trials	Warm up ~ 6 trials with each club; Driver, 5-iron and pitching wedge	No significant difference in swing phase time or left knee flexion between driver and 5-iron but the kinematics and CHS differed between clubs. However, a significant difference ($p < 0.05$) between driver and 5-iron and pitching wedge with right knee joint flexion at ToB exists.
Fedorcik et al. [45] (Moderate)	Average of all 7 trials.	Self-directed	Warm up ~ Static calibration ~ 7 participant approved trials with a 5-iron	High versus low handicap groups had less lead arm (left) radial deviation at ball contact ($p = 0.008$) and a more acute angle of descent when forearm was parallel ($p = 0.001$).
Ferdinands et al. [46] (Weak)	5 trials with the highest BS out of 10 trials.	Practice trials	Warm up ~ Static calibration ~ 10 trials with a 5-iron	No correlation of either X-factor or X-factor stretch to CHS
Healy et al. [34] (Moderate)	3 trials with the highest BS out of 15.	Practice trials	Warm up ~ 15 trials with their own 5-iron.	Significant difference of pelvis rotation at early DS ($p = 0.002$), mid DS ($p = 0.008$), and X-factor at early DS ($p = 0.007$), mid DS ($p = 0.002$), ball contact ($p = 0.001$) and mid follow-through ($p = 0.002$) between high and low BS groups.

Author (Quality)[a]	**Trials analysed**	**Warm-up protocol**	**Experimental protocol**	**Outcome measures and results**
Horan et al. [60] (Weak)	All 5 trials		5 trials with their own driver	Females have significantly higher thorax rotation at ball contact ($p = 0.02$), and pelvis rotation at mid DS ($p = 0.01$) and ball contact ($p = 0.04$) than males. However, both sexes illustrate low CH variability.
Horan et al. [61] (Weak)	All 5 trials	Standardised 10 min warm-up[68] ~ practice trials	Warm up ~ 5 trials with their own driver	No significant difference between sex and X-factor variables. At ball contact males have less thorax axial rotation ($p < 0.01$), less pelvis rotation ($p < 0.01$), greater lateral tilt velocities ($p < 0.01$), greater pelvis lateral tilt ($p<0.01$) and greater CHS ($p < 0.01$) compared to females.
Horan et al. [36] (Weak)	All 5 trials	Standardised 10 min warm-up[68] ~ practice trials	Warm up ~ 5 trials with their own driver	Strong coupling method between pelvis and torso ($r^2 = 0.99 \pm 0.01$), significantly ($p < 0.05$) higher than head and thorax coupling $r^2 = 0.83 \pm 0.17$. Used as simplification method for ensuring consistent motor pattern control.
Joyce [29] (Strong)	3 trials with the highest CHS out of 5	Standardised 5min warm up ~ practice trials	Warm up ~ 5 trials with their own driver and 5 trials with their own 5-iron	Trunk and lower trunk X-factor ($r = 0.84$, $p < 0.01$) and X-factor stretch ($r = 0.71$, $p = 0.01$) were positively correlated with CHS for the 5-iron but not the driver. Strong positive correlation exists between lower trunk X-factor stretch and CHS ($r = 0.78$, $p < 0.01$). Moderate negative correlation between lateral trunk bending at ball impact and CHS ($r = -0.61$, $p =0.02$).
Joyce [53] (Strong)	3 trials with the highest CHS out of 5	Standardised 5min warm up ~ practice trials	Warm up ~ 5 trials with their own driver	Strongest positive association to CHS were; lower trunk maximum axial rotation ($\beta = –.52$, $p < .01$), lower trunk axial rotation at ToB ($\beta = .34$, $p < .01$), trunk axial rotation at the ToB ($\beta = .28$, $p < .01$) and lower trunk left axial rotation flexibility ($\beta = .23$, $p < .01$).
Joyce et al.[37] (Moderate)	3 trials with the highest CHS out of 5		Static calibration ~ ROM trials ~ 5 trials with their own driver	No significant difference between clubs for angular velocity trunk kinematics and CHS. The variable most positively related to CHS for the 5-iron was maximal axial rotation of the lower trunk ($\beta = -0.665$) and lower trunk flexion/extension at ToB for the driver ($\beta = 0.340$).

Author (Quality)[a]	**Trials analysed**	**Warm-up protocol**	**Experimental protocol**	**Outcome measures and results**
Joyce et al.[58] (Moderate)	3 trials with the highest CHS out of 5.	Indoor and outdoor familiarisation practice trials	Familiarisation ~ 5 trials with experimental driver	High kick point driver resulted in delayed in wrists release (4.3% later, 0.044 s) during DS and lower launch angle (*p* = 0.005). Wrist kinematics explained (67% and 60%) of the variance in CHS between the high and low kick point drivers.
Joyce et al. [56] (Moderate)	Median 3 CHS trails were average out of 5		5 trials with their own driver	Trunk crunch factor ($p < 0.01$), lower trunk axial rotation velocity ($p < 0.05$) and lower trunk crunch factor ($p < 0.05$) have a significant positive association with CHS.
Kwon et al. [38] (Moderate)	All 5 trials		5 trials with their own driver	No significant correlation between X-factor or X-factor stretch with CHS
McNally et al. [43] (Weak)	Trial with highest CHS of 8.	Self-directed	Warm up ~ 8 trials with a driver	Strong positive correlation between total lower extremity work and CHS ($r = 0.63$).
Meister et al. [44] (Weak)	2 trials with the best reconstructed 3D data quality out of 3		3 trials at each effort (easy, medium, and hard) with their own 5-iron	Strong positive correlation between X-factor at impact (0.943), peak X-factor (0.900), and peak shoulder axis tilt (0.900) to CHS amongst professional golfers at impact.
Myers et al. [35] (Weak)	5 highest CHS trials out of 10.	Self-directed ~ practice trials	Warm up ~ 10 trials under 3D analysis with participants own driver.	A moderate correlation ($r > 0.5$, $p < 0.001$) between BS and increased X-factor, X-factor stretch, maximum upper torso rotation velocity, and X-factor velocity.
Sorbie et al. [30] (Weak)	All 5 trials	Dynamic stretches ~ 5 practice trials	Warm up ~ 5 trials with a TaylorMade driver ~ practice session (50 shots with the TaylorMade driver and 50 shots with a TaylorMade 7-iron at a rate of 2 a minute) ~ 5 trials with a TaylorMade driver	Significant increase in X-factor ($p = 0.00$), X-factor stretch ($p = 0.02$), CHS ($p = 0.00$), BS ($p = 0.01$), and CD ($p = 0.00$) following a practice session.

Author (Quality)^{a}	Trials analysed	Warm-up protocol	Experimental protocol	Outcome measures and results
Steele et al. [42] (Moderate)	All 3 at each different effort	Self-direct ~ practice trials	Warm up ~ 3 trials at each effort (easy, medium, and hard) using their own 5-iron (for professionals). Amateur performed 2 trials at a perceived effort of hard using their own 5-iron	Peak upper-torso velocity ($p = 0.005$), peak X-factor ($p = 0.005$) and pelvis velocity ($p = 0.019$) is reduced in amateur compared to professionals.
Zheng et al. [57] (Moderate)	2 trials the participant deemed to be the best out of 10		10 trials with their own drive	Significant difference in maximum angular velocity between right & left wrist of male and females ($p = 0.001$ & $p = 0.001$) relative to CHS ($p = 0.001$).
Zheng et al. [41] (Weak)	2 trials the participant deemed to be the best out of 10		10 trials with a driver.	Significantly higher ($p < 0.05$) angular velocities (deg/s) in right shoulder internal rotation, left and right elbow extension, and left and right wrist between professionals and high handicap amateurs. Increased proximal rotation velocity resulted in increased club shaft angular velocity in professionals.

Notes. ^{a}, Effective Public Health Practice Project quality assessment score; BS, Ball speed; CD, Carry distance; CH, Clubhead; CHS, Clubhead speed; DS, Downswing; HBS, High ball speed; LPGA, Ladies professional golfers association; PGA, Professional golfers association; TD, Total distance; ToB, Top of backswing; ~, Followed by.

3.4 3D data collection methods

The studies reviewed implemented different 3D data collection protocols. Sixteen studies[29,30,34,36-38,43,44,53-56,58-61] used the VICON infrared camera system and six[17,41,42,44,45,57] used the Motion Analysis system. Data capture frequencies ranged from 50 to 500 Hz, with 240 Hz ($n = 7$)[17,41,42,44-46,57] and 250 Hz ($n = 6$)[29,30,34,37,38,53] being the most common sampling frequencies. Studies implemented a variety of marker placement methods. The total amount of markers ranged from 9 to 65 markers. Most commonly, the markers where place on C7, T10, left and right anterior superior iliac spines, left and right posterior superior iliac spines, suprasternal notch, left and right acromioclavicular joints, and clubhead and/or shaft to reconstruct in 3D the motion of the torso, pelvis, and club.

3.5 Warm up strategies

The warm-up strategies implemented by the 23 studies varied. Six studies[29,30,36,53,54,61] used a prescribed warm-up (i.e., defined structure and duration) that included static and dynamic stretching. Five studies[35,42,43,45,55] allowed the participants to do a self-driven warm-up, and seven studies[37,38,41,44,56,57,60] did not state warm-up parameters. Over half of the studies ($n = 12$)[17,29,30,34,36,42,46,53,54,58,59,61] allowed participants to have practice trials to familiarise themselves with the testing environment and equipment prior to experimentation, whereas familiarisation was not stated or completed in the other 11 studies.

3.6 Biomechanical variables

Multiple biomechanical variables were assessed across studies, but nearly all studies ($n = 22$)[17,29,30,34-38,41-44,46,53-61] investigated the effects of either the pelvis, torso, or pelvis-torso angular separation (i.e., X-factor) on golfing performance. A positive correlation with clubhead speed was found for pelvis-torso coupling[36,54,55,58], upper and lower torso interaction[37,53], and lower body work[43]. However, the nature of the association between pelvis and torso measures and clubhead speed were inconsistent in the literature reviewed. Seven studies[29,30,34,35,42,44,53] found a positive correlation between X-factor measures and clubhead speed, whereas three studies[38,46,61] reported no association.

Five studies[38,41,45,57,58] assessed the influence of wrist biomechanics on performance. Peak angular velocity of both the lead and trail wrists was seen to be up to 63.9% and 67.1% faster in professional and low handicap golfers compared to high handicap amateurs[41,45]. Additionally, a significant ($p < 0.01$) difference in peak angular velocity of both the lead and trail wrists were seen between male and female professional golfers[57].

Discussion

This review critically examines and summarises research surrounding golfing biomechanics and performance based on 3D motion analysis methods. Within the 23 articles appraised, only two[36,53] were deemed to be of a strong methodological quality in accordance with the EPHPP checklist. The cohorts of high level amateur (n = 311) to professional (n = 140) golfers were predominantly males (81%). Clubhead (n = 20 studies) and ball speed (n = 10 studies) were the most common variables used to monitor performance. From these investigations, biomechanical variables that positively related to performance in the long game, specifically increased clubhead speed, were pelvis and torso rotation, pelvis and torso rotation velocity during the downswing, pelvis-torso coupling, X-factor measures, and wrist and arm angular velocity.

4.1 Pelvis and torso

The biomechanics of the pelvis and torso was assessed by 96% of the 23 articles appraised. The pelvis and torso have large degrees of axial rotation ranging from 43.1° to 63.2° for the pelvis and 83.5° to 108.0° for the torso in males at the top of the backswing[59]. Findings from Joyce et al.[53] suggest that skilled golfers have increased axial rotation and that enhancing pelvis-torso rotational flexibility is important for improving golf performance within skilled male golfers. These recommendations agree with findings that professional golfers produce increased pelvis and torso rotational velocity during the downswing and at impact than amateurs[42], thought to result from the better coordinated action of the pelvis and torso (pelvis and torso coupling and X-factor measures)[36,54].

4.2 X-factor

X-factor measures define the rotational angular separation between the pelvis and the torso, and is typically measured at the top of the backswing[29]. X-factor is a measure frequently reported in golf biomechanics literature[29,38], and believed to reflect use of the stretch shortening cycle (SSC). More specifically, the backswing is used to develop elastic potential energy via the stretch and separation of the pelvis, lower thoracic region, and upper thoracic region[69]. The elastic potential created during the backswing is then converted into kinetic energy during the rapid uncoiling of the body during the downswing phase. However, the amount of elastic potential energy developed through the X-factor does not necessarily ensure a direct increase in clubhead and ball speed, as is suggested by the literature here reviewed. Of the ten studies reviewed[29,30,34,35,38,42,44,46,53,61] pertaining to the X-factor; Seven[29,30,34,35,42,44,53], including the two methodologically strong studies, found a positive correlation between X-factor and clubhead speed. One of the studies of strong methodological quality found that three X-factor related flexibility variables and six golf swing kinematic variables were significantly related to clubhead speed[53]. That said, three studies[38,46,61] found no correlation between the X-factor at the top of the backswing and clubhead speed.

Disagreement also exists in the literature on whether X-factor values differ between female and male golfers of the same skill level[57,61]. However, as a golfers skill level lessens, smaller X-factor values are seen in both sexes[34,35]. Sorbie, Gu, Baker, Ugbolue [30] showed that following a practice session, the X-factor (pre: 52.82 ± 5.64°, post: 54.06 ± 5.61°, $p = 0.00$) and X-factor stretch (pre: 1.54 ± 1.05°, post: 1.90 ± 1.41°, $p = 0.02$) increased significantly, which was paralleled by a significant increase in clubhead (pre: 103.6 ± 4.85 mph, post: 105.32 ± 4.61 mph, $p = 0.02$) and ball (pre: 147.77 ± 9.29 mph, post: 149.64 ± 8.3 mph, $p = 0.01$)[30] speed. The authors concluded that performing multiple golf swings results in an increase in X-factor and long game performance[30]. However, relying on the X-factor value alone as a measure of golfing performance is not recommended, especially given the multiple marker set[70] and computational methods used[38,46] and significant impact that computational methods can have on X-factor values[70].

A variety of marker sets were used across the literature here reviewed (see **Table 2**), ranging from 9 to 65 markers. Kwon et al.[38] identified a significant difference ($p < 0.001$) in X-factor values between three X-factor computational methods at ball impact in a population of highly-skilled golfers. The conventional method provided comparable or slightly larger X-factor values than reported in previous reseach[41,71], but the other two X-factor methods resulted in lower values. Furthermore, Kwon et al.[38] found no direct correlation between X-factor parameters and maximum clubhead speeds, except for finding a positive association between X-factor velocities at the top of the backswing and normalised maximum clubhead speeds ($p < 0.05$) when using the conventional method to calculate the X-factor. Although X-factor parameters might be useful in establishing a golfer's skill level, one cannot presume that an increase in the angular separation between the pelvis and torso will directly influence clubhead speed without a fundamental understanding of additional swing characteristics[38] and considering computational method.

4.3 X-factor stretch

An additional X-factor measure extracted from 3D golf biomechanics analysis is the maximal separation between the pelvis and torso, known as the X-factor stretch. The X-factor stretch occurs during the initial portion of the downswing phase as the pelvis begins to rotate towards the target while the torso is still rotating away from the target[16,30,46,72]. The X-factor stretch is commonly seen from the 3D analysis of high level amateur or professional players in an attempt to increase the SSC to enhance performance[26,73,74]. The high level amateur and professional golfers included in this review had X-factor stretch values between 1.1 and 4.1°. Eight studies[29,30,34,35,38,44,46,53] investigated the topic and report diverging results in terms of its relationship to clubhead speed. Meister et al.[44] investigated the influence of different swing efforts (easy, medium, and hard) on X-factor measures. It was concluded that X-factor stretch, X-factor at impact, and peak upper-torso rotation were highly consistent and positively related to clubhead speeds at impact. These findings align with those of five other studies[29,30,34,35,44,53] that found a positive correlation between X-factor stretch and clubhead speed. Research from Joyce[29] showed that lower trunk X-factor stretch explained 74% of the variance in 5-iron clubhead speed of 15 skilled participants (handicap < 2.5 ± 1.9). Contradicting these results were studies from Ferdinands et al.[46] and Kwon et al.[38] in which no correlation between X-factor stretch and clubhead speed was detected. Again, the diverging results between studies are potentially due to variations in X-factor stretch computation methods[38]. As such, it is still unclear whether X-factor measures are determinants of power generation and golf swing performance. It could be that at a given level, there is a plateau in terms of the effectiveness of the X-factor and X-factor stretch to enhance clubhead speeds further.

4.4 Additional golfing performance measures

Three studies[41,45,57] reported an association between wrist variables and swing performance. However, within the studies reviewed, the correlation between radial and ulnar deviation to clubhead speed and participant skill level was inconsistent. Zheng et al.[41] found no relation between the amount of radial deviation of golfers and their skill level, but this study was of weak methodological quality. Fredorick et al.[45] noted lesser radial wrist deviation in players with a superior skill level in a study of better methodological quality. These authors concluded that lesser-skilled golfers relied on radial deviation to a greater extent to compensate for a lack of shoulder, torso, and pelvic rotation[45]. That said, the literature reviewed overall suggests that maximal wrist angular velocity plays an important role in long game performance. Players with a increased skill level delay the point at which maximal wrist angular velocity occurs during the downswing phase[32,41,45,57], indicating that maximal wrist angular velocity happens closer to the time of ball impact. Reaching maximal wrist angular velocity later in the downswing phase is a technique recognised as being critical in reaching high clubhead speeds[32].

Segment sequencing was reported in four articles[41,46,57,59] with differences seen in relations to the ‘classical’ proximal to distal sequencing. The classical proximal to distal sequencing refers to the pelvis, torso, arms and club initiating and reaching maximal angular velocity in successive order during the downswing[75]. Significant differences in segment rotational timings during the downswing were reported to exist between skill levels[41]. Professional golfers positioned both their lead and trial arms beside their trunk from horizontal abduction earlier in the downswing, and extend the right elbow and increase lead wrist angular velocity closer to ball contact than amateurs[41]. In amateurs, proximal segments reach maximal velocities closer to ball contact than in professionals[41]. Findings from Ferdinands et al.[46] differed from the other three articles reviewed[41,57,59] with high level amateur golfers (handicap < 2.0) not adhering to the classical proximal to distal segment sequencing. However, this research had a small sample size (5 participants) and was of weak methodological quality.

4.5 Limitations

One limitation existing within the golf biomechanics literature is that 91% of the studies were performed in a laboratory environment. The other 9% did not state the testing environment. Swinging a golf club indoors does not entirely reflect the demands of the game on course, and provides a limitation if the participants perceive the environment as stressful or not ecologically valid[76,77]. With the lack of information about warm-up strategies and practice trials in 43% of the studies reviewed, it is unclear if participants had sufficient time to familiarise themselves with the laboratory environment. Movement variability also exists within golf. A participants' set-up can vary even when the task and conditions are constant[32]. Movement patterns between male and female golfers have also been shown to differ[57,60,61,78]. For example, females create larger angular rotation in both the pelvis and torso in comparison to males[57,60,78], whereas males exhibit greater left knee flexion[78] and increased wrist angular velocity during the downswing phase[57]. Langdown et al.[32] further explains that the demands of golf require the individual to produce different swing mechanics in relation to the desired length, direction, and ball trajectory, as well as specific ground conditions. Furthermore, the optimal coordination pattern in golf is likely individual specific due to each individual's constraints in movement[79]. Therefore, there is potentially a considerable amount of intra-subject and inter-subject variability that exists in terms of golf swing mechanics that affects the ability for research to identify metrics consistently associated with performance. The variance between studies in terms of marker sets, computational methods, and sampling frequencies makes it difficult to combine data from the various available studies for strong cross-study inferences.

Conclusion

Twenty-three articles were appraised as part of this systematic review focusing on 3D analysis of golf biomechanics. From these studies, the most consistent biomechanics measures significantly related to clubhead and ball speed were pelvis and torso measures. Specifically, pelvis and torso axial rotation, rotational velocity, X-factor, and X-factor stretch were positively associated with golfing performance. Of consideration is the fact that only two[36,53] of the 23 articles were deemed to be of a strong methodological quality, with most studies conducted in laboratories on male golfers. These observations highlight the need for studies of stronger methodological quality to be undertaken in ecologically valid environments, and include female participants.

Chapter Two: Literature Review – Effect of a Weighted Equipment Warm-Up on Ball Striking Performance

Abstract

Introduction:

Ball striking sports are using weighted equipment as part of warm-ups as a means of enhancing subsequent swing performance through potentiation. This literature review aimed to critically appraise and summarise the research on weighted equipment used during warm-ups and its effect on subsequent performance.

Methods:

The Pubmed, Scopus, and Web of Science electronic databases were searched on the 13th December 2018 using the search syntax "Weighted equipment AND Sport AND (Performance OR Biomechanics)". Only original research using weighted sports equipment in preparation for sporting performance (i.e., warm-up) to enhance subsequent ball-striking performance were included. The methodological quality of articles was assessed using a modified version of the Effective Public Health Practice Project (EPHPP) tool.

Results:

Seven studies met inclusion. All articles addressed the sport of baseball, with most (*n* = 6) being of weak methodological quality. Eighteen heavier and nine lighter than standard bats (range: 272.2 to 2721.5 grams, -68.8 to +211.9% of standard bat mass) were used by 161 participants as part of warm-up. The weighted mean baseline bat speed of participants was 66.21 ± 14.21 mph. Twenty-four of the twenty-seven weighted bats used as part of warm-ups either significantly decreased or were ineffective in altering subsequent bat speed.

Conclusion:

The use of weighted equipment warm-up as a means to enhance subsequent swing performance was ineffective or even detrimental in relation the baseball batting speed. Only one article of the seven appraised was of strong methodological quality according to the EPHPP quality assessment tool. The lack of research in ball striking sports outside of baseball and the generally weak quality of articles in the area highlight the need for better quality studies in different ball striking sports.

Introduction

Ball striking sports comprise of an array of team and individual sports, including – but not limited to – baseball, softball, field hockey, badminton, cricket, lacrosse, tennis, table tennis, and golf[80,81]. All ball striking sports share a common swing phase that involves the control of biomechanically complex movement patterns within a short time period with the aim of striking a moving or stationary object using an implement[82]. For example, baseball requires an athlete to wind up, decide to swing, and accelerate a bat to contact a moving baseball all within a 400 to 500 ms timeframe during which time a pitch is released and arrives to the plate[83]. The baseball batter has between 150 to 200 ms to accelerate the bat to speeds exceeding 34.3 m/s or 76.7 miles per hour (mph) to contact the baseball after deciding to swing the bat[83]. By decreasing the time it takes to reach peak bat speed, an athlete has more time to analyse a pitch and decide whether to swing the bat or not. The additional time taken to analyse the pitch allows the batter to better gage the speed, potential movement in space, and likely location of the ball over the plate, increasing the likelihood of the rigid bat to contact the ball with the desired swing outcome[84,85].

Professional golf players regularly exceed clubhead speeds of 49.2 m/s or 110 mph[29,30,36-38] during the swing phase. Increasing clubhead speed can have a pronounced effect on the golf ball speed and distance, ultimately resulting in low golf scores and increasing the likelihood of a golfer to win[4]. Although enhancing bat speeds in other ball striking sports like baseball can also improve sporting performance, increasing clubhead speed might have a more direct impact on swing performance and outcomes in golf given that the player does not need to react to a moving object as the ball is stationary. Given the link between swing phase mechanics and performance in ball striking sports; coaches, athletes, and sports scientists are continuously trialling various intervention methods to improve performance, including the use of different warm-up strategies prior to competition.

1.1 Warm-ups in ball striking sports

Ball striking sports demand time specific whole-body kinematic chain sequencing for performance[16,86-88]. Within these sports, the swing phase requires high levels of joint flexibility, range of motion, and control of multiple degrees of freedom in space[22,23,86,89]. The golf swing is an example of a motion in which multi-joint coordination pattern is required. Proximal to distal segment sequencing is important to maximise ball speed and distance during the golf swing[90]. The readiness of an athlete to perform the complex actions required within the golf swing depends on an appropriate warm-up. Gelen et al.[91] demonstrated how different warm-ups affect tennis serve performance. The incorporation of static stretching into an individual warm-up routine had no effect on tennis serve performance[91]. However, the use of either dynamic or plyometric warm-ups increased serving velocity measures[91]. In golf, incorporating static stretching into a warm-up has been shown to decrease driving performance in professional and elite amateur players[89,92,93]. The varied effect of warm-ups on performance across sports emphasises the importance of developing a ball striking specific warm-up strategy that targets the swing phase mechanics to ensure the individual is ready to perform.

1.2 Active and passive warm-up strategies

An active warm-up can be defined as physical activity performed prior to competition or training with the purpose of enhancing performance[94]. Active warm-ups historically comprised of low intensity aerobic exercise, most commonly followed by static or dynamic stretching[93] and then sport-specific exercises[95]. Passive warm-up strategies rely on an outside factor contributing to heating of muscles and other anatomical structures[96,97], such as the use of warm water immersion, heated vests or blankets, and additional layers of clothing[98]. Passive warm-up methods have been shown to improve cycling sprint performance measures by 2 to 5% in competitive athletes[98-100]. However, these methods are now more frequently used to maintain the physiological benefits of active warm-ups during the transition period between warm-up and competition[98,99]. Intensity[101], duration[102], type of exercise or intervention[103], and delay between warm-up and performance[104] are reported to influence the effect of warm-ups on performance.

Combining these different components to optimise performance in a given sport is challenging, with numerous studies attempting to understand how best to integrate these various components in a warm-up to improve performance[96]. Two of the main underlying mechanisms of active and passive warm-ups relate to temperature and neural priming.

1.3 Temperature mechanisms

Both active and passive warm-up strategies have demonstrated an improvement in sport performance due to an increase in muscle temperature[98,99], with an increase of 1°C enhancing exercise performance by 2 to 5% depending on the type and velocity of muscular contraction involved[100]. In ball striking sports, post warm-up temperature increases enhance the swing phase by improving an individual's range of motion[105] and contractile velocity of type II muscle fibres[106]. With an elevated temperature, type II muscle fibres are better able to use phosphocreatine (PCr) and adenosine triphosphate (ATP), which increases maximal power output[107] and improves performance during exercises involving high contractile velocities[107-109]. Additionally, the time to reach peak twitch reduces as muscle temperature increases, improving muscle fibre conduction velocity[108,110]. Muscle fibre conduction velocity does not only improve during the contraction phase at increased temperatures, but also during relaxation[111]. These data suggest that rate of force development and relaxation are temperature dependant, with increased muscle temperature being better, up until a point dependant on exercise and environmental factors[112].

1.4 Neural mechanisms

Recent activation of skeletal muscles can significantly influence the subsequent force that same muscle can generate, which is known as post activation potentiation (PAP)[113,114]. The force a muscle is able to generate post activation is a result of the net balance between fatigue and potentiation[115-117]. When the net balance favours potentiation or when fatigue has dissipated and potentiation remains, an acute improvement in muscle performance occurs[116-118]. Multiple muscle and neural mechanisms have been linked to the improvement in performance through PAP[119].

These mechanisms include enhanced central output of motor neurons via the elevated transmittance of excitation potentials across synaptic junctions at the spinal cord[116,117,120], as well as enhanced myosin regulatory light chains (RLC) phosphorylation that improves the interaction between myosin and thick and thin filaments[116,121]. Furthermore, RLC phosphorylation makes the actin-myosin interaction more sensitive to myoplasmic Ca^{2+} [116,117,122]. PAP inducing exercises have been shown to enhance performance of activities that are of short duration with high contractile velocities (e.g., sprinting[123-125] and jumping[126-128]), as well as of longer duration with slower contractile velocities (e.g., middle and long distance running)[114,117,129-131]. PAP inducing exercises normally comprise of heavy resistance exercises (e.g., > 85% of 1 repetition maximum), like bench presses[132], back squats[123,125], horizontal sled pulls[133], and Olympic lifts[134,135] depending on the targeted activity. However, the practicality and feasibility of using these exercises for PAP within a sporting context is limited to high performance environments, prompting the emergence of research inducing PAP through the use of body weight exercises, such as depth jumps[136,137] or plyometrics with light loads[138,139].

1.5 Weighted equipment warm-ups in ball striking sports

Weighted equipment is being used as part of warm-ups in ball striking sports to incorporate a sport-specific activity that readies the body for performance. For instance, weighted baseball bats, ice hockey sticks, cricket bats, tennis racquets, and golf clubs are used in warm-ups or as part of training given that they require similar biomechanical movement patterns as the sport demands[118,127,140-142]. Baseball most commonly uses weighted equipment within warm-ups via specifically designed bats with altered mass, weighted gloves, or the addition of a donut (weighted rubber ring) to a standard bat. Research surrounding the effects of baseball bat swings post warm-up following the use of weighted bats, gloves, or donuts reports varying effects on performance[85,143-148], with most of the research indicating ineffectiveness or even detrimental effects of using weighted equipment as part of warm-ups on baseball swing velocities.

Performance in ball striking sports depends on the velocity and/or accuracy of the swing phase due to the whole-body, time-specific kinematic chain sequencing required. With the continued production, promotion, and use of weighted equipment in ball striking sports, it becomes vital to understand better its influence on performance. Therefore, the aims of this systematic review of the literature was to critically appraise and summarise the research on weighted equipment used during warm-ups in ball striking sports and its effect on performance.

Methods

2.1 Systematic search

This systematic review followed the structure and reporting requirements of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement[49]. The Pubmed, Scopus, and Web of Science electronic databases were systematically searched on the 13th of December 2018 using the search syntax "Weighted equipment AND Sport AND (Performance OR Biomechanics)". Articles needed to meet the following inclusion criteria:

1. Use of weighted sports equipment during a warm-up in preparation for performance.
2. Weighted equipment should intend to influence the primary sports movement pattern and its influence upon an object (i.e., ball striking sports).
3. Have a performance driven aim.
4. Involve healthy participants with no previous injury history that could influence movement patterns.
5. Be an original research article published in a peer-reviewed journal.
6. Be available in the English language.

One reviewer (GLW) conducted the three database searches and collected all articles in a reference manager software (Endnote, version X9, Clarivate Analytics, Philadelphia, PA, USA). Duplicate articles from the database searches were removed before inclusion and exclusion criteria were used to screen the titles, abstracts, and full-text articles in that order. A second independent reviewer (KHL) verified the results from the screening process. Two additional articles were identified through supplementary searches of reference lists of included articles. No additional articles were found through supplementary searches of publications by key authors and other databases (i.e., Google Scholar and SPORTDiscus). The search strategy and article selection process are illustrated in **Figure 3**.

2.2 Quality assessment

A modified version of the Effective Public Health Practice Project (EPHPP) checklist was used to quality assess the articles meeting inclusion given that no specific quality assessment tool has been designed for sport science. The 14-item EPHPP quality assessment tool was chosen for this review given it suited the study design of articles meeting inclusion[50,51], has demonstrated reliability[50,51], and has been used in review of sport science literature previously[52]. The standardised template of the EPHPP score sheet was adapted to incorporate confounders of importance specific to this review (sex, skill level, and age in section C). An additional grade of "missing data" was also added to the withdrawals and drop outs in section F. If the study design did not incorporate an intervention, a grade of "Fair" was allocated to blinding of the outcome assessors in section D.

Two reviewers (GLW and IH) met before independently quality assessing the articles to agree on how to score each item based on the EPHPP checklist manual. After independent assessment, the two reviewers met to discuss disagreements and achieve a consensus rating. A third reviewer (KHL) was identified to resolve any differences in opinion, but was not required. The final quality assessment score was calculated as recommended by the EPHPP scoring guidelines. A study was allocated an overall quality rating of "strong" if none of the major components were rated as weak, "moderate" if only one major component was rated as weak, or "weak" if two or more of the components were rated as weak.

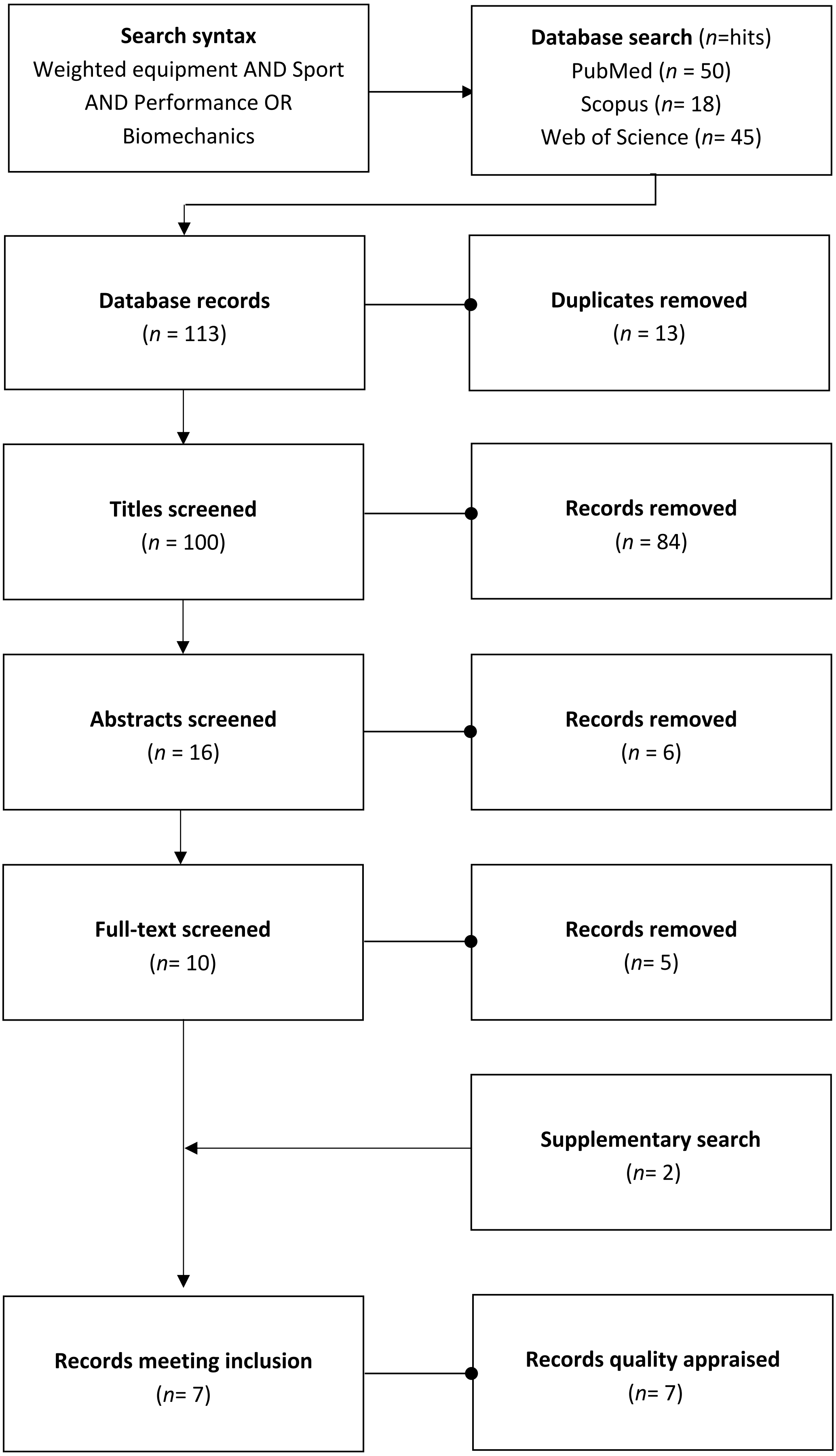

Figure 3. Flow diagram of article selection process.

2.3 Data extraction

Information concerning study aims, sport, weighted equipment, participants, anthropometrics, skill level, warm-up methods, experimental protocol, data collection methods, swing and body variables measured, performance measures, and key findings were extracted from each article using a standardised format by one reviewer (GLW). Completeness of data extraction was verified by a second reviewer (KHL).

2.4 Data analysis

Data were managed and analysed using Microsoft Excel 2016 (Microsoft Corporation, Redmont, WA, USA). Descriptive statistics for the data were expressed using means and standard deviations (mean ± SD), ranges (minimum to maximum), counts (*n*), or percentages (%) depending on data type. When appropriate, weighted means based on sample size were calculated for height, mass, and age of participants, as well as performance measures for sport-specific variables.

Results

3.1 Quality assessment

The quality scores from the modified EPHPP checklist are presented in **Table 3** for the seven studies meeting inclusion. One study was deemed to be of strong methodological quality[143], and the remaining six were methodologically weak[85,144-148] based on the EPHPP quality appraisal tool.

Table 3. Effective Public Health Practice Project (EPHPP) quality appraisal score for each of the assessed articles (*n* = 7).

Article	**Representative of study population**	**% of participants agreed to partake**	**Study design**	**Difference between groups at baseline**	**% of relevant confounders controlled**	**Assessors aware of intervention**	**Participants aware of research question**	**Valid**	**Reliable**	**Data drop-outs reported**	**% participants completion**	**Score**
DeRenne et al.[148]	Somewhat likely	?	Cohort	N	> 80%	?	?	?	Y	N	> 80%	Weak
Higuchi et. al[143]	Somewhat likely	?	Cohort	N	> 80%	?	?	Y	Y	Y	> 80%	Strong
Montoya et. al[144]	?	?	Cohort	N	> 80%	?	?	?	Y	N	> 80%	Weak
Ohta et. al[147]	Somewhat likely	?	Cohort	N	> 80%	?	?	?	?	N	> 80%	Weak
Reyes & Dolny[85]	Not likely	?	Cohort	N	60 – 79%	?	?	?	?	N	> 80%	Weak
Southard et. al[145]	Not likely	?	Cohort	N	> 80%	?	?	?	?	N	> 80%	Weak
Szymanski et. al[146]	Somewhat likely	?	Cohort	N	> 80%	?	?	?	?	N	> 80%	Weak

Notes. N, No; Y, Yes; ?, Cannot tell.

3.2 Participant characteristics

All seven studies[85,143-148] aimed to investigate the potential influence of using weighted equipment as part of a warm-up on bat speed and performance in baseball. In the weighted equipment literature, "performance" was defined as the ability to maximise bat speed while maintaining control of the strike on the baseball. All seven studies[85,143-148] were cohort studies with a single group. Across the seven studies, 161 healthy participants were included, with an average sample size of 23 ± 17 (range: 7 to 60). Of the 161 participants, 102 (63%) were male and the sex of the remaining 59 participants (37%) was not specified. Male participants were 1.82 ± 0.04 m tall, 86.51 ± 4.58 kg in body mass, and 21.97 ± 2.11 years old. Key characteristics of the seven studies are shown in **Table 4**.

Participant skill levels were categorised into three sub groups, consisting of recreational (12%), intermediate (40%), and expert (48%) based on current competitive performance levels. Weighted equipment literature defined recreational as the absence of participation in the current competitive season, intermediate as participation in high school or age group competitive sport, and expert as participation in college or professional sport.

3.3 Data collection methods

Data collection methods differed between the studies reviewed. Five studies[85,143,144,146,148] used light emitters and sensors to record the time. The timer starts and stops when the bat strikes the first and second light beams, respectively. The distance between the light beams ranged between 0.03 to 0.45 m. The remaining two studies[145,147] incorporated 3D motion analysis systems. The 3D data capture frequencies ranged from 200 to 400 Hz, with the only marker set stated using eight markers (see **Table 4**).

3.4 Weighted equipment variables

In the seven studies[85,143-148], a standard bat was used and was 84.1 ± 0.8 cm long and 872.6 ± 43.3 g in mass for baseline and post warm-up measures. Baseline measures of bat speed for the standard bat were 29.60 ± 6.35 m/s or 66.21 ± 14.21

mph. The weighted baseball equipment used ranged from 83.8 to 86.4 cm in length and 272.2 to 2721.5 g in mass (-68.8 to +211.9% of standard bat mass). Across the seven studies[85,143-148], 27 weighted bats were examined. Nine were lighter than standard and 18 were heavier. Five studies[85,144-146,148] investigated the effects of using a lighter bat on performance (84.0 ± 0.0 cm and 635.0 ± 197.5 g), and all seven studies[85,143-148] investigated the effects of using a heavier bat (84.0 ± 0.7 cm and 1460.1 ± 395.4 g). Additional key characteristics of studies are presented in **Table 4**.

3.5 Effects of weight equipment warm-up on performance

Of the nine lighter than standard baseball bats used during warm-up, six bats[85,144-146,148] resulted in no significant change in batting speed, while one bat[148] resulted in a significant ($p < 0.05$) decrease in performance. Only two of the lighter bats[148] resulted in a significant ($p < 0.05$) increase in bat speed in comparison to bats that were more than 10% heavier or lighter than standard. Of the 18 bats heavier than standard[85,143-148] (range: 963.9 to 2721.5 g), 10 bats[143-145,148] resulted in a significant ($p < 0.05$) decreases in baseball bat speed, six bats[85,146] resulted in no change, one bat[147] significantly ($p = 0.02$) increased timing error, and one bat[148] significantly ($p < 0.05$) increased bat speed in comparison to bats that were more than 10% heavier or lighter than standard. Participants perceived the standard bat as light and fast after the completion of a heavy bat warm-up[147,149] despite no recorded improvements in performance. Additional characteristics of weighted baseball bat characteristics and effect on swing speed are presented in **Table 4**.

Table 4. Characteristics of studies using weighted equipment as part of warm-ups in ball striking sports (*n* = 7).

Article (Quality)[a]	**Sport**	**Warm-up equipment**	**Participants**	**Data collection method**
DeRenne et al.[148] (Weak)	Baseball	8 heavy bats: 1.76, 1.64, 1.45, 1.36, 1.28, 1.19, 0.96, 0.96 kg 1 standard bat: 0.85 kg; 4 light bats: 0.82, 0.77, 0.71, 0.65 kg All 13 bats: 83.8 cm and aluminium	60 males Age: 16 to 18 y Level: Intermediate	Photo sensing computerised timer. Sensors set 10.16 cm apart.
Higuchi et. al[143] (Strong)	Baseball	1 heavy bat: 0.85 kg + 0.68 kg wrap (total 1.53 kg) 1 standard bat: 0.85 kg Both bats: 83.8 cm (aluminium)	24 males Height: 1.83 ± 0.06 m Mass: 84.0 ± 12.5 kg Level: Expert	Photo sensing computerised timer (BatMaxx 5500). Sensors set 3 cm apart.
Montoya et. al[144] (Weak)	Baseball	1 heavy bat: 1.57 kg (0.89 kg aluminium bat + 0.68 kg donut) 1 standard bat: 0.89 kg (aluminium) 1 light bat: 0.27 kg (plastic) All 3 bats: 83.8 cm	19 males Height: 181.1 ± 8.4 cm Mass: 87.9 ± 18.4 kg Age: 24.5 ± 3.9 y Level: Recreational	Photo electric sensors (Model E3Z; Ormrod electronics). Capture frequency: 10000 Hz. Sensors set 45 cm apart.
Ohta et. al[147] (Weak)	Baseball	1 heavy bat: 1.2 kg, 85 cm 1 standard bat: 0.85 kg, 86 cm	7 males Height: 176.4 ± 6 cm Mass: 76.0 ± 5.8 kg Age: 21.3 ± 0.8 y Level: Expert	3D Motion Analysis Corporation using 20 infrared cameras. Capture frequency: 400 Hz. Marker set: not specified.

Article (Quality)^a	**Sport**	**Warm-up equipment**	**Participants**	**Data collection method**
Reyes & Dolny[85] (Weak)	Baseball	1 heavy bat: 1.53 kg (0.85 kg bat + 0.68 kg wrap) 1 standard bat: 0.85 kg 1 light bat: 0.79 kg All 3 bats: 83.3 cm and aluminium	19 participants Age: 20.15 ± 1.46 y Level: Recreational	Infrared photocell control boxes. Sensors set 30.48 cm apart.
Southard et. al[145] (Weak)	Baseball	1 heavy bat: 1.59 kg (0.96 kg bat + 0.63 kg donut) 1 standard bat : 0.96 kg 1 light bat: 0.34 kg (plastic) All 3 bats: 83.8 cm	10 males Age: 20 to 25 y Level: 60% expert, 40% intermediate	Watsmart motion analysis system. Data collection area 2 x 2 m. Marker set: 8 markers, bat, L&R styloid process, L&R lateral epicondyle, L&R glenohumeral axis and sternoclavicular notch.
Szymanski et. al[146] (Weak)	Baseball	5 heavy bats: (1) 2.72 kg, 86.4 cm, (2) 1.53 (0.85 kg aluminium bat + 0.68 kg wrap), (3) 1.30 (0.85 kg aluminium bat + 0.45 kg donut), (4) 1.25 kg (0.85 kg aluminium bat + 0.4 kg power fins), (5) 0.96 kg (wooden) All bats 83.8cm 1 standard bat: 0.85 kg, 83.8 cm (aluminium) 2 light bats: (1) 0.74 kg (83.8 cm aluminium), (2) 0.63kg (88.9 cm, aluminium)	22 males Height: 182.6 ± 8.3 cm Mass: 91.4 ± 11.4 kg Age: 20 ± 1.5 y Level: Expert	Light emitting sensor and reflector, SETPRO SpRT5A chronograph was used to detect BBS, Sensors set 10.16 cm apart.

Notes. ^{a}, Effective Public Health Practice Project quality assessment score; BBS, Baseball bat speed; L&R, Left and right; NS, Not specified.

Table 4 *(continued)*. Characteristics of studies using weighted equipment as part of warm-ups in ball striking sports ($n = 7$).

Article (Quality)[a]	**Warm-up protocol**	**Experimental protocol**	**Outcome measure and results**
DeRenne et al.[148] (Weak)	Stretching 1 minute ~ 4 maximum velocity swings with weighted implement (random)	Warm-up ~ 3 standard bat swings (20 s rest) attempting to generate maximum velocity	Bats between 0.77 and 0.96 kg increased velocities (+0.6 m/s and +0.1 m/s, $p < 0.05$) Very LM (0.65 kg) and very HM (1.64 kg) decreased velocities (-1.9 m/s and -2.0 m/s, $p < 0.05$)
Higuchi et. al[143] (Strong)	3 maximum velocity swings with weighted implement (5 s rest between swings)	Warm-up ~ 60 s rest ~ 3 standard bat swings, batting a ball off the tee at maximum velocity (10 s rest) compared to baseline measures	No significant change in post-SM BBS (-0.33 m/s), significant decrease in post-HM BBS (-0.89 m/s, $p = 0.05$), significant increase post-isometric BBS (+0.39 m/s, $p = 0.05$)
Montoya et. al[144] (Weak)	5 maximal velocity swings with weighted implement (random)	Warm-up ~ 30 s rest ~ 5 standard bat swings attempting to generate maximum velocity	Post warm-up HM BBS (41.79 ± 3.01 mph) significantly decreased compared to SM (51.25 ± 3.01 mph) and LM (63.57 ± 3.58 mph) BBS ($p < 0.05$)
Ohta et. al[147] (Weak)	3 maximal velocity warm-up swings with weighted implement (random)	A simulated object was projected towards the participants on LED's with changing position and velocity. Participant performed 30 swings (6 swings x 5 blocks) with a standard bat	Timing error increased when a simulated change in ball speed occurred in the post HM warm-up ($p = 0.024$)
Reyes & Dolny[85] (Weak)	6 maximal velocity swings with each weighted implement (18 swings total, 3 to 5 s rest between swings)	Warm up ~ 30 s rest ~ 5 standard bat swings (30 s rest) attempting to generate maximum at a soft tossed pitch	No significant difference in BBS across conditions

Article (Quality)[a]	Warm-up protocol	Experimental protocol	Outcome measure and results
Southard et. al[145] (Weak)	Stretching + 5 maximum velocity swing with weighted implement (15 s rest between swings, random)	Warm up ~ 2 min rest ~ 5 standard bat swings attempting to generate maximum velocity	BBS was significantly decreased post HM warm-up ($p < 0.001$). No significant difference between SM and LM
Szymanski et. al[146] (Weak)	3 maximum velocity swings with weighted implement (random)	Warm up ~ 2 swing with standard bat ~ 3 standard bat swings (20 s rest) attempting to generate maximum velocity while hitting a ball off a tee	No significant difference in BBS across conditions

Notes. [a], Effective Public Health Practice Project quality assessment score; BBS, Bat speed; HW, Heavier than standard bat mass; LED, Light-emitting diode; LW, Lighter than standard bat mass; SW, Standard bat mass; ~, Followed by

Discussion

This review critically examined and summarised research surrounding the influence of weighted equipment used during warm-up on subsequent performance in ball striking sports. All seven articles appraised implemented a one group cohort study design, with only one article[143] deemed to be of strong methodological quality in accordance with a modified version of the EPHPP checklist. All seven[85,143-148] articles researched the influence of using weighted equipment during warm-up on baseball bat speed, with no articles addressing other ball striking sports. Overall, there is limited evidence that using equipment of lighter mass in warm-ups meaningfully affects swing performance. In terms of heavier equipment, most of the evidence suggests that using heavy weighted equipment as part of ball striking warm-up has detrimental or no effects on subsequent swing velocity, questioning the appropriateness of using weighted bats as part of warm-ups to improve performance.

4.1 Weighted equipment within warm-ups

Six[85,143-147] articles reviewed concluded that a weighted baseball bat warm-up significantly decreased or did not change performance. Previous research on PAP reports increases in power output with transition times from PAP to performance between 2 to 18.5 minutes[140,150], with 4 to 12 minutes being optimal in high-level athletes[127,135,141,151-155]. While the potentiation of the muscle twitch is greatest immediately following a PAP stimulus, the net balance between fatigue and performance varies over time[156]. Any enhancements in performance is no longer meaningful 30 minutes post stimulus[141,151,157]. The seven articles[85,143-148] assessed as part of this review employed a transition time between the weighted bat warm-up and performance of 47 ± 39 seconds (range: 20 to 120 s). These timeframes were likely insufficient to mitigate the fatigue experienced post-weighted bat warm-up due to the depletion of phosphocreatine (PCr) during muscle contraction[85,107]. The resynthesis of the PCr stores requires 4 to 8 minutes to reach a sustainable level[154,158,159]. We suggest that the short transition times (< 120 s) implemented by the weighted baseball bat studies were insufficient for PCr resynthesis. As such, the performance tests subsequent to the weighted bat warm-up occurred while the net balance between fatigue and potentiation favoured fatigue, nullifying the PAP performance enhancing potential. As such, the application of PAP within baseball using weighted equipment is limited and warrants further investigation with longer transition times.

Heavy resistance exercises increase recruitment of type II fast twitch muscle fibres[127,140-142,160]. Type II fast twitch muscle fibres are reported to exhibit greater PAP responses compared to other muscle fibres[161]. Individuals with more than three years of resistance training experience respond better to PAP inducing exercises, presumably due to their experience limiting the amount of muscle damage caused by PAP inducing loads[151]. A meta-analysis on PAP by Wilson et al.[151] suggests that the ideal load to induce PAP is between 60 to 84% of one-repetition maximum (1RM) independent of training experience. However, within baseball research, findings support that an increase or decrease of more than 10% in bat mass changes batting biomechanics[145,148]. The pursuit of PAP with the use of weighted equipment, using an equipment that is more than 10% heavier or lighter than a standard bat mass may ultimately be detrimental to the athlete due to the use of a different biomechanical movement pattern than that required during performance. In the seven studies reviewed[85,143-148], 93% of the weighted bats were either lighter or heavier than the standard bat mass by more than 10%. The fact that a majority of bats used were more than 10% heavier or lighter than standard and potentially involved different biomechanical patterns than observed during the swing phase might explain the overall lack of a positive association between the use of weighted equipment during warm-ups and subsequent performance.

The use of a lighter than standard baseball bat during warm-ups is based on overspeed training theories more than PAP. Overspeed training involves the use of an external stimulus to allow an individual to surpass maximal velocities normally achieved during the sporting task[162]. Overspeed training is most commonly applied in sprinting, with external stimuli such as downhill running and assisted towing significantly improving an athlete's acceleration and maximum velocity[163-165]. The equivalent in ball striking sports is the use of lighter than standard equipment. Five studies[85,144-146,148] used baseball bats lighter than standard, with three bats[85,148]

(0.79, 0.77 and 0.82 kg) having a mass within 10% of standard bat mass. Of these three bats used during a warm-up, two bats significantly increased bat speed compared to bats that were more than 10% lighter or heavier than standard[148].

4.2 Weighted equipment used in performance

Studies have examined the effects of using weighted equipment on swinging performance itself, rather than subsequent a warm-up[82,147,166]. Laughlin[82] and Ohta et al.[147] compared batting performance on a simulator using bats with different moments of inertia or mass. The findings from both studies suggest that an increase in either inertia or bat mass negatively influences bat speed and ball striking performance. Whiteside et al.[166] analysed the 3D biomechanics of youth tennis players serving with an increased racquet mass, finding a moderate decrease in swing velocity and no change in ball speed with an increase in racquet mass[166]. All three[82,147,166] studies showed an immediate decrease in performance variables with an increase in implement mass.

It has been previously stated that as implement mass or moment of inertia increases, an athlete may select an alternative biomechanical movement pattern to complete the task[145] that potentially differs from the task's optimal biomechanical patterning. This phenomenon was evident in the tennis serving research conducted by Whiteside et al.[166] where an increased in racquet mass impeded internal rotation and wrist flexion, which are the two biomechanical contributors to resultant racquet speed at ball impact[166,167]. These biomechanical changes reflect a reorganisation of how the degrees of freedom are used to complete the task[166]. The influence of increased clubhead mass on golfing performance has also been examined, with an increase in clubhead mass resulting in a significant decrease in clubhead speed and total distance, and increase in total ball spin and lateral dispersion ($p < 0.01$)[168]. The increase in implement mass during the swing phase of ball striking sports alters the impact location, timing, delivery, and velocity of the implement[166], decreasing the energy transferred to the ball. As such, coaches and athletes should bear in mind that using heavy equipment as part of warm-up and training is likely to alter biomechanical movement patterns.

4.3 Isometric PAP inducing exercise

Higuchi et al.[143] investigated the effects of PAP induced using either high-intensity isometric exercises designed to replicate the early swing phase in baseball batting or weighted equipment. Participants performed alternating sets (four total) of 5 s efforts pulling with the lead arm and pushing with the trail arm for the isometric exercises[143]. Unlike the weighted bat warm-up (**Table 4**), the isometric PAP resulted in a significant increase in bat speed (0.39 m/s, $p < 0.05$)[143]. A similar study of PAP inducing isometric exercise was completed with experienced female softball players with varying rest periods between isometric contraction and performance testing[169]. Softball bat speed was elevated above baseline after isometric warm-up at 2, 4, 6, 8, 10, and 12 minutes post isometric PAP[169]. PAP warm-ups are suggested to enhance muscular performance when the phosphorylation of myosin regulatory light chains (RLCs) exceeds the time needed for repletion of phosphagen stores in muscles[116]. As previously stated, PCr stores require 4 to 8 minutes to resynthesise[154,158,159], while the phosphorylation of myosin RLCs dissipates around 12 minutes depending on training level[170,171]. As such, it appears that performance benefits for induced isometric PAP exercises range from 4 to 12 minutes, which is supported by previous research demonstrating transition times between 4 to 12 minutes as optimal for performance enhancements subsequent a PAP stimulus[127,135,141,151-155].

4.4 Limitations

Although the aim of this review was to critically appraise and summarise research on weighted equipment used during warm-ups in ball striking sports and its effect on performance, only baseball studies were identified. The generalisation of weighted equipment warm-up strategies and their effect on performance from baseball studies to other ball striking sports is limited due to the swing phase of each sport occurring in different planes of motion and relying on specific biomechanical movement patterns. For example, the swing phase in baseball takes place predominantly in the transverse plane, whereas the vertical plane dominates in golf. Furthermore, the ball is stationary in golf, but dynamic in baseball. The effectiveness of PAP is also suggested to be linked with training experience, wherein individuals with more resistance training experience benefit from PAP inducing exercises to a greater extent due to a more favourable balance between fatigue and potentiation[151]. The seven studies reviewed[85,143-148] reported the sporting level of their baseball athletes, but not their resistance training experience. Furthermore, six of the studies[85,144-148] were of weak methodological quality and there was large discrepancies in warm-up protocols (i.e., transition times and weighted equipment used), suggesting that better methodological quality studies in different sports with resistance trained athletes are warranted to determine whether weighted equipment in warm-ups benefit ball striking sport performance.

Conclusion

In total, seven articles[85,143-148] were quality assessed as part of this systematic review on the use of weighted equipment during warm-up on subsequent performance in ball striking sports. All articles focused on baseball, with 86% of them being of weak methodological quality. Overall, the use of weighted equipment as a method to enhance subsequent swing phase performance was ineffective or even detrimental in terms of bat speed. The lack of research in ball striking sports outside of baseball and the generally weak quality of articles in the area highlight the need for better quality studies in different ball striking sports.

Chapter Three: Experimental Study – Acute Effects of a Weighted Club Warm-Up on Golf Performance and Biomechanics

Abstract

Introduction:

Increasing financial incentives associated with improved tournament performance in golf has led to the use of various warm-up strategies to enhance clubhead speed, included the use of weighted clubs to induce post activation potentiation (PAP). This research aimed to investigate the effect of the SuperSpeed weighted club warm-up protocol on clubhead speed, ball speed, and swing biomechanics.

Methods:

3D motion analysis (500 Hz) was used to investigate swing biomechanics of 12 golfers (handicap < 3.0) in a cohort study design comparing a golf-specific control warm-up to the SuperSpeed warm-up. Swing, X-factor, peak angular velocity, and centre of mass (COM) parameters were compared between conditions using Cohen's standardised effect size (ES).

Results:

Clubhead speed; angular velocity of the torso, lead arm, and club; and COM at the top of backswing in the target direction (x) and in the posterior direction (left of the target, y) at impact showed a significant ($p < 0.05$) *small* (ES > 0.2) and likely (greater than 75% likelihood) change after use of the SuperSpeed versus control warm-up protocol. However, no significant change was seen in ball speed, resulting in a *moderate* negative change in the smash factor (ES -0.80, $p = 0.008$).

Conclusion:

Using the SuperSpeed warm-up protocol significantly influenced COM and peak angular velocities, increasing clubhead speed by 2.6 mph. No significant changes were seen in X-factor variables despite previous research associating increased X-factor variables with increased clubhead speeds. Our findings suggest that the SuperSpeed warm-up protocol does not significantly change ball speed despite PAP enhancements in clubhead speeds, likely due to the lack of familiarity with changes in biomechanical patterning.

Introduction

The financial income of professional golfers are amongst the highest in athletes, with five players from the Professional Golfers Association (PGA) featuring in Forbes 100 list of the World's highest-paid athletes in 2018[172]. Even more impressive is that only 12 athletes from this list of 100 athletes competed in individual-based sports (i.e., boxing, golf, mixed martial arts, tennis, and track), indicating that 42% of the top-paid individual-sport athletes in the World were golfers in 2018. There is hence considerable financial incentive to improve golf performance. Within the last 20 years, the winner's purse for one of the most contested golf tournament (i.e., PGA Championship) has increased by 214.3% to a total value of 1.98 million American dollars[3].

With enhancements in technology, equipment, physical preparation, and golf swing biomechanics; golfing performance based on weighted scoring average[8,9] is now more strongly correlated to the long game (> 91.44 m or 100 yards) than the short game (< 91.44 m or 100 yards)[6,12,14,15,17,18]. Analyses of PGA tour data collected from 2003 to 2010 comprising of over 8 million golf shots illustrate that the long game explains over two-thirds of the variation in scores between PGA tour competitors[14]. Players, coaches, and sport scientists are using biomechanical tools to analyse the downswing phase of the long game in detail, with clubhead speeds exceeding 110 miles per hour (mph) or 49.2 m/s [16,26,29,30,36-38]. The generation of high clubhead speeds is of particular interest due to its strong correlation to skill level, handicap, and scoring average[24,47,48,173,174].

Differing warm-up strategies are being implemented in ball striking sports (e.g., baseball, softball, field hockey, badminton, cricket, lacrosse, tennis, table tennis, and golf)[80,81], primarily targeting temperature and neural factors. These warm-up strategies include the use of passive warm-up methods such as warm water immersion, heated vests or blankets, and additional layers of clothing[98]. More commonly, active warm-up strategies are used and typically comprise of low intensity aerobic exercises, static or dynamic stretching[93], and sport-specific exercises[95]. Ball striking sports are trying to further enhance performance with the integration of various weighted equipment during active warm-ups and in training, as seen through the use of weighted baseball bats[85,143-148], ice hockey sticks[175], cricket bats[176], tennis raquets[177], and golf clubs[178]. The value of using heavier equipment as part of warm-ups is suggested to rely on post-activation potentiation (PAP) mechanisms to enhance subsequent performance, whereas the use of lighter equipment further relies on overspeed mechanisms.

The acute performance enhancement effects of PAP derive from the net balance between potentiation and fatigue, favouring potentiation in recently activated muscles[113-118]. The acute performance improvements with PAP, particularly in activities involving high contractile velocities (e.g., sprinting[123-125,135] and jumping[126-128]), are due to the enhancement of myosin regulatory light chains (RLC) phosphorylation[179] and elevated neural excitability[117,119]. In sports, PAP is generally induced via the incorporation of a resistance exercise eliciting a similar biomechanical movement pattern to the activity requirements[118,127,135,140-142,180]. Gym-based resistance exercises are therefore adapted in an attempt to replicate the musculature and neural recruitments needed during the sport in question[92], which might not be highly specific to the sporting task . Weighted bats in baseball, sticks in hockey, and SuperSpeed clubs in golf are the closest equivalent of PAP-inducing activities that replicate sport-specific demands[118,140], which are as specific to the sporting task as possible. Baseball literature has incorporated the use of heavier bats during warm-ups as a method to enhance subsequent swing performance. This method has proven ineffective or even detrimental in terms of subsequent batting velocity[85,143-148], challenging the use of weighted equipment as a warm-up strategy for ball striking sports. An increase of more than 10% in bat mass has been shown to alter batting biomechanics and significantly decrease batting speed by as much as 2.6 m/s[145,148]. Therefore, the pursuit of PAP using heavy equipment greater than 10% of standard weight may be detrimental to an athlete’s performance, as observed in baseball.

In contrast, the use of lighter than standard striking implements during warm-ups is based on the theory of overspeed training. Overspeed training involves the use of an external stimulus to allow an individual to surpass normal maximal velocities produced during the specific sporting task[162]. Overspeed training is commonly seen in sprinting with the incorporation of downhill[163,164,181] or band assisted[165] running. Baseball has used bats lighter than standard in an attempt to provide an overspeed stimulus. Similar to the use of heavier bats, bats lighter than 10% of standard mass have been shown to alter biomechanics and decrease batting velocity[145,148]. However, the use of baseball bats lighter than standard, but within 10% of standard mass, have been associated with non-significant increases in bat speed up to 0.6 m/s[148], indicating a potential for improved performance.

In golf, different warm-up strategies to improve performance have been researched, including static[68,89] and dynamic stretching[92,182], dynamic warm-ups[92,183,184], and resistance band exercises[92,183]. These warm-ups have been shown to positively influence acute driving distance[92,182], centeredness of strike[182], and clubhead speed[68,185]. Limited research has attempted to incorporate PAP or overspeed into a golf-specific warm-up. Read et. al.[186] researched the relationship between clubhead speed and the use of a countermovement jump (CMJ) to induce PAP. The use of three CMJs pre-golf swing produced a significant increase (2.25 mph, $p < 0.05$) in clubhead speed after resting for one minute[186]. Although the biomechanical demands of the CMJ may differ to the rotation involved in the golf swing, incorporating an exercise requiring the recruitment of fast-twitch muscle fibres during the warm-up led to an acute improvement in golfing performance in this particular investigation[186].

SuperSpeed Golf™ (Chicago, IL) has designed a set of weighted clubs (SuperSpeed Golf Training System) to be used by golfers in warm-up and training to enhance clubhead speed. The warm-up protocol requires athletes to progress in swing intensity using the different weighted clubs[178]. SuperSpeed Golf™ claims 600 top touring professionals are using their product, including Phil Mickelson prior to major competitions, such as the US Open[187,188]. The incorporation of a more golf-specific exercise to induce PAP may lead to a greater increase in clubhead speed and performance than that seen with CMJs[186]. Therefore, the aim of this study was to investigate the acute effects of using SuperSpeed clubs and recommended warm-up protocol on golf driving performance and biomechanics in high level amateur golfers compared to a control golf-specific warm-up condition.

Methods

2.1 Participants

Sample size requirements were calculated from standard two-tailed hypothesis equations[189], an 80% power ($\beta = 0.20$), 5% significance level ($\alpha = 0.05$), critical values of the *t*-distribution, and test-retest reliability data on clubhead speed from previous studies[28,190]. These calculations indicated that 7 to 11 participants were needed to identify reported minimal detectable mean changes (3.7 to 6.9 mph) in clubhead speeds with corresponding standard deviations (3.1 to 4.6 mph) at the 5% significance level with 80% power. To account for potential withdrawals or missing data, 12 participants were targeted.

Twelve competitive golfers (7 males, 5 females) volunteered to participate (**Table 5**) and completed the experiment. All participants were right-hand dominant; hence, for all participants, the lead arm and hip refer to the left-hand side of the body and the trail arm and hip refer to the right-hand side. The inclusion criteria were: minimum of 16 years of age, free from any injuries, were actively involved in, and had at least one year of resistance training experience, and registered with a New Zealand golf handicap of less than 3.0 (due to high skilled amateur golfers having a reduced level of movement variability[32]). Participants were excluded if not meeting these inclusion criteria. Participants were recruited via electronic emails sent to current representative players of the following associations: Bay of Plenty Golf, Waikato Golf, and New Zealand Golf. All participants were informed about the potential risks and benefits of study participation, and were required to provide written informed consent. The testing protocol was approved by the Human Research Ethics Committee of the University of Waikato [HREC (Health) #2018-35], followed international ethical standards[191], and adhered to the Declaration of Helsinki

Table 5. Participant characteristics (mean ± standard deviation).

Characteristic	Male (*n* = 7)	Female (*n* = 5)	Total (*n* = 12)
Height (cm)	179 ± 8	166 ± 7	174 ± 10
Body mass (kg)	77.9 ± 18.2	64.9 ± 8.6	72.5 ± 15.8
Age (y)	23.7 ± 8.3	19.6 ± 3.8	22 ± 6.9
Current handicap	0.4 ± 1.8	1.0 ± 2.0	0.6 ± 1.8
Experience (y)	13.4 ± 8.1	9 ± 5.9	11.5 ± 7.3
Time spent playing golf (h/week)	15.4 ± 15.3	16.5 ± 7.3	15.9 ± 12.2

Notes. All participants were right-hand dominant.

Prior to the first testing session, participants completed a baseline questionnaire on golf experience, practice routines and anthropometric characteristics were recorded. Participants also rated their prior experience with SuperSpeed clubs as none (*n* = 9), low (*n* = 2), moderate (*n* = 1), and high (*n* = 0).

2.2 Experimental protocol

A one-group within-subject repeated measures cohort study was used to investigate the effect of warm-up condition (control versus SuperSpeed) on golf swing performance and biomechanics, with participants randomly assigned an order to complete the two conditions. Each warm-up condition was completed on two different days, at a similar time of day, within a 10-day period. Each participant was familiarised with the testing procedure before experimentation. Participants performed all golf swing testing trials using their own golf shoes and drivers.

The control warm-up was designed to replicate the habitual warm-up routine that players would perform in preparation to tournament play (**Figure 4**). The control warm-up required participants to swing their own clubs in progression of sand wedge, 9-iron, 6-iron, 3-iron (or 4-iron), and driver a total of five times each on their dominant side with a 30 s rest between clubs. The SuperSpeed warm-up (**Figure 4**) followed the manufacturer's recommendations and used the SuperSpeed clubs (**Figure 5**). The SuperSpeed clubs used during the warm-up are different for males and females (**Figure 5**); however, the protocol remains the same with participant progressing intensity, load, and speed throughout the warm-up (**Figure 4**). The male SuperSpeed clubs were 23.53% lighter (light club), 8.62% lighter (medium club) and 9.24% heavier (heavy club) than the typical driver weight, 315 grams[192].

After the completion of the designated warm-up, participants completed their normal pre-shot routine, followed by swinging their own driver once. The researcher was thereby able to recognise players pre-shot routines and determine when to start the 3D motion capture system. After a 90 s rest period, the data collection trials began. Each participant was instructed to complete their normal pre-shot routine prior to each recorded trial and hit the golf ball “as far as possible” into the middle of the driving net using their natural golf swing. Participants would complete five trials at a rate of one swing every 30 to 60 s depending on each participant’s pre-shot routine.

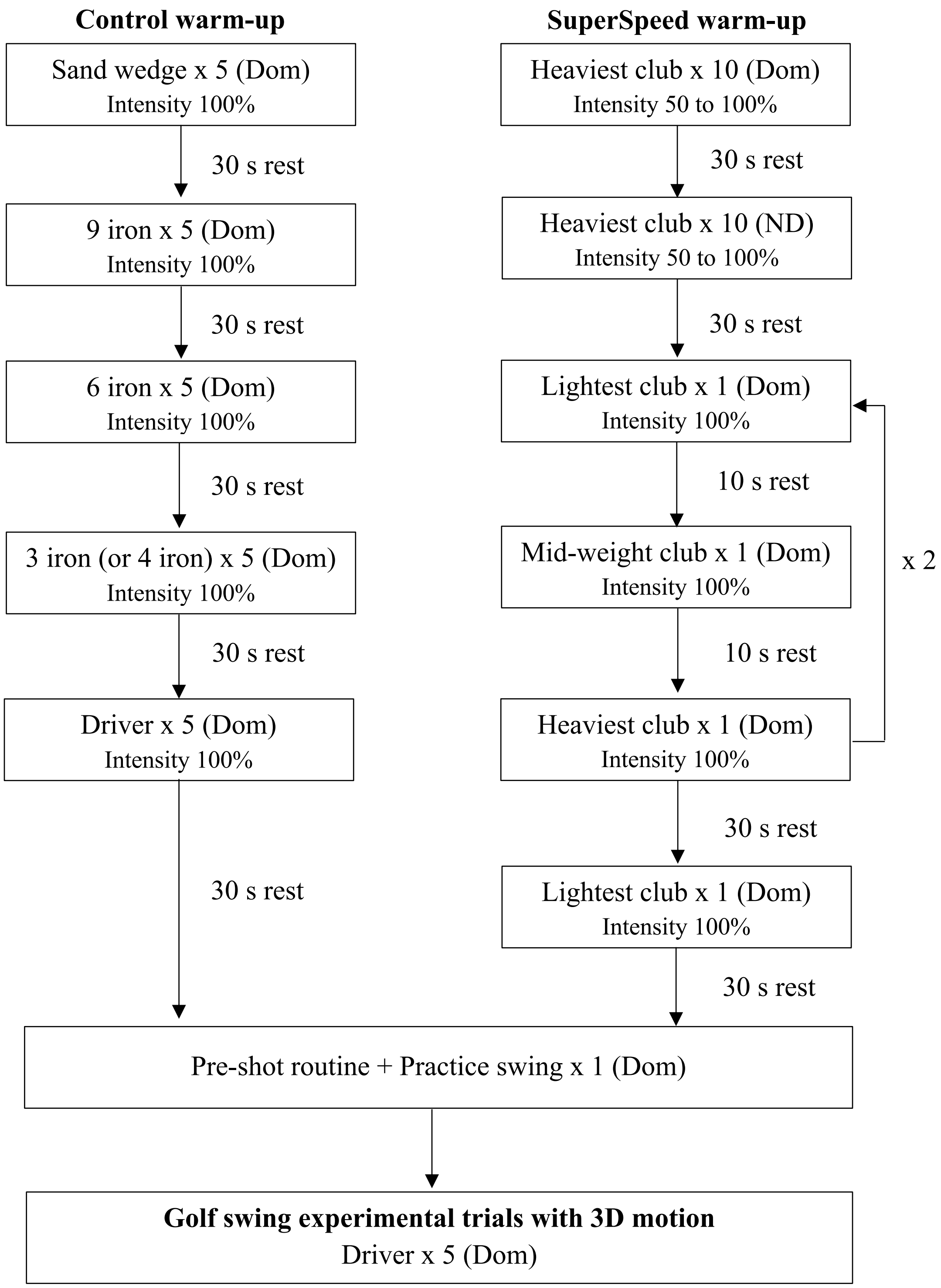

Figure 4. Flow diagram of control and SuperSpeed warm-up protocols for a right-hand dominant golfer. Dom, dominant: represents right-hand swings; ND, non-dominant: represents left-hand swings.

Club		Mass (g)		Protocol	
Name	**Colour**	**Stated[a]**	**Actual[b]**	**Male**	**Female**
Super light	Yellow	225.0	233.7		✓
Light	Green	255.0	261.9	✓	✓
Medium	Blue	290.0	297.6	✓	✓
Heavy	Red	335.0	341.0	✓	

Note. All clubs are 114.3 cm in length.
[a] Mass stated by the manufacturer SuperSpeed Golf™ (Chicago, IL).
[b] Mass measure using Precisa XT6200C Instrument Ltd., Switzerland.

Figure 5. SuperSpeed clubs, characteristics, and protocol for males and females.

2.3 Data collection

Testing was completed in a laboratory environment using a practice driving mat, with participants hitting towards a net placed 5.5 metres away from the tee (**Figure 6**). Participants used their own driver and new 2018 Titleist Pro V1 golf balls covered in reflective tape. Kinematic data were collected using the Qualisys Track Manager version 2.17 (build 4000), Golf Performance Visual3D Project Automated Framework version 4.0.1+66, one video camera (Oqus 210c) capturing at 50 Hz, and 10 infrared motion capture cameras (8 Oqus 700+, 2 Oqus 310+, Qualisys AB, Gothenburg, Sweden) capturing at 500 Hz. Prior to each session, the capture volume was calibrated using a 601.5 mm calibration wand and an L-frame that defined the Cartesian origin of the laboratory. The X-axis of the virtual laboratory was aligned with the target direction (+ towards target), Y-axis was perpendicular to the target direction (+ to the right of the target), and Z-axis was aligned with vertical (+ superior). From an initial golf-swing set-up position for all of our right-hand dominant participants, movements towards the target in the X-direction represented movements towards the lead (+ left) side, and movements towards the right of the target in the Y-direction represented movements towards the tee (+ forward). Each participant stood in the middle of the calibrated volume for 1 s to allow static calibration and case-specific model definition prior to the warm-up protocols. The local coordinates of all segments were derived from this static measurement.

Fifty-six 12.5 mm in diameter retro-reflective markers were affixed to participants (*n* = 50 makers) and the club (*n* = 6 markers) using Tesa® 4965 double-sided tape, Fixomull® stretch adhesive non-woven fabric, and Mastisol® liquid adhesive following guidelines from the Golf Performance Visual3D Project Automated Framework (**Figure 6**). The golf ball was also covered in reflective tape to track the ball. Markers were placed on participants on the following locations: front, left, and right head; bilateral acromial edges, posterior and anterior upper arms, humeral lateral epicondyles, radial styloid processes, and ulnar styloid processes; leading forearm, supra wrist, and 3rd metacarpal head; bilateral supra (7th cervical region) and infra (4th thoracic region) upper back; bilateral iliac crests, anterior superior iliac spines, posterior superior iliac spine, and infra posterior superior iliac spines; bilateral posterior and anterior thighs, femoral lateral and medial epicondyles, tibial tuberosities, lateral and medial malleoli, calcanei, and 5th and 2nd metatarsal heads. For the club, four markers were spaced 5 cm apart on the shaft starting 5 cm below the grip, with markers also attached to the heel and toe of the clubface. Markers on the lead arm ulnar styloid process, iliac crests, anterior superior iliac spines, and clubface were removed once the static trial was completed.

From the marker set, a 14-segment biomechanical model with 6 degrees of freedom at each joint was constructed in Visual3D Professional™ Software version 6.01.36 (C-Motion, Germantown, MD) to model participants. Segments included the head, upper arms, lower arms, lead hand, torso pelvis, thighs, shanks, and feet, from which the centre of mass (COM) of individuals was derived based on mechanical principles and Dempster's regression equations[193]. The upper end of the torso was defined using the acromial edges and the lower end of the torso based on the iliac crest markers[194], and a CODA pelvis was used to define the hip joint centres[195]. In addition, three segments were constructed to define the clubface, clubhead, and ball.

Figure 6. Participant in static position with full marker set prior to completing a warm-up condition with graphical representation of the virtual lab direction.

2.4 Data processing

Marker data for all golf swing experimental trials were exported to the C3D format and processed in Visual3D Professional^{TM}. The swing was broken down into six time points: takeaway (clubhead velocity exceeds 0.1 mph), half back (lead arm is horizontal), top of backswing, angular velocity of the club reaches zero), half down (lead arm is horizontal), impact (frame before clubhead passes ball position in the X-direction), and follow-through (clubhead reaches its maximum height after impact)[196]. Marker data were interpolated using a least-squares fit 3rd order polynomial, and filtered using a 4th order 6 Hz Butterworth bidirectional filter except for the lead arm and club markers. To account for discontinuities in marker trajectories at impact, post-impact samples were replaced by a linear extrapolation of the clubhead path to avoid endpoint artefact[197]. The downswing phase data were subsequently filtered at 10 Hz, follow-through at 25 Hz, and backswing at 10 Hz. For the purpose of this study, only the downswing phase (from top of backswing to impact) was of interest.

Kinematic parameters were calculated using rigid-body analysis and Euler angles obtained from the static calibration. Body angles in the sagittal (flexion–extension), coronal (adduction–abduction), and transverse (internal–external rotation) planes were calculated using an *x-y-z* Cardan sequence equivalent to the Joint Coordinate System. Pelvis and torso angles in the sagittal (anterior–posterior and flexion–extension), coronal (lead, left and trial, right side), and transverse (dominant, non–dominant rotation) planes were defined relative to the laboratory using an *z-y-x* Cardan sequence based on work from Baker[198]. X-factor angles were also calculated using an *z-y-x* Cardan sequence, and defined the separation of the torso in relation to the pelvis around the Z-axis[70]. A negative angle indicated the torso rotated away from that target in relation to the pelvis during the backswing or the pelvis leading the torso (rotated towards the target) during the downswing.

2.5 Parameters

Swing, X-factor, angular velocity, and COM parameters were of primary interest based on biomechanical literature on golf[17,29,30,34-38,41-44,46,53-61,70]. More specifically, swing variables of interest included: clubhead peak speed during downswing ($\mathrm{CHS_{peak}}$, mph); clubhead impact speed ($\mathrm{CHS_{impact}}$, mph); time between $\mathrm{CHS_{peak}}$ and $\mathrm{CHS_{impact}}$ (ms); resultant ($\mathrm{Ball_{peak\_R}}$), anterior-posterior ($\mathrm{Ball_{peak\_X}}$), medial-lateral ($\mathrm{Ball_{peak\_Y}}$), and superior-inferior ($\mathrm{Ball_{peak\_Z}}$) golf ball velocity (mph), smash factor ($\mathrm{Ball_{peak\_R}/CHS_{peak}}$); backswing, downswing, and follow-through times (ms); and downswing (backswing time: downswing time) and follow-through (follow-through time: downswing time) ratios. X-factor variables extracted were: X-factor peak, at top of backswing, and at impact (°); difference between X-factor peak and impact (°), and X-factor peak and X-factor at top of backswing (X-factor stretch, °); and time between X-factor peak and impact, and X-factor peak and top of backswing (ms). Peak rotational angular velocities of the pelvis, torso, lead arm, and club (°/s), and timing of these peaks in relation to ball impact (ms) were also extracted. Finally, COM variables extracted from the data were: COM position at impact, at top of backswing, and at its lowest vertical position during the downswing phase in relation to position at takeaway in the laboratory *x-y-z* directions (cm); difference in COM position between impact and its lowest vertical position, and top of backswing and its lowest vertical position (cm); and COM linear displacement velocity at impact in the laboratory *x*-*y*-*z* directions (cm/s). Since participants were directed to hit the ball into the middle of the net placed 5.5 m away, information regarding club path and ball dispersion were not analysed as deemed an inaccurate reflection of performance in relation to game demands.

2.6 Statistical analysis

Means and standard deviations (mean ± SD) were computed for all parameters. Changes in mean and standardised effect sizes (ES) were computed to compare the effect of warm-up condition on the parameters of interest. The ES was considered *small, moderate, large,* and *very large* when reaching absolute threshold values of 0.2, 0.6, 1.2, and 2.0, and trivial when < 0.20[199]. An effect was deemed 'clear' when it's 95% confidence limit (CL) did not overlap the thresholds for small positive and small negative effect (i.e., 5%), and 'likely' to be clinically meaningful when its probability exceeded 75%[199]. Paired *t*-tests were used to investigate differences between warm-up conditions with the threshold for statistical significance set at $p < 0.05$. Data were analysed using customised statistical spreadsheets (Microsoft Excel 2016, Microsoft Corp, Redmond WA, USA). Only non-trivial, clear, likely, significant effects were deemed to reflect a meaningful biomechanical change. Results were summarised using tables. Key figures of results are also provided as appendix (Appendix 2, Figures S1 – 4).

Results

3.1 Swing parameters

After completing the SuperSpeed warm-up, CHS_{peak} (102.8 ± 10.1 mph) and CHS_{impact} (102.5 ± 10.4 mph) were significantly ($p < 0.001$) and likely (more than 75%) faster (ES 0.26 and 0.24) than the control warm-up protocol CHS_{peak} (100.2 ± 9.7 mph) and CHS_{impact} (100.0 ± 9.7 mph). However, this difference in CHS did not translate to a meaningful change in ball speed resulting in a *moderate* meaningful decline in smash factor (ES -0.80, $p = 0.008$, **Table 6**). In terms of timing characteristics, there was a *small* (ES -0.22), clear (more than 75% likely), and significant ($p < 0.001$) decrease in downswing time with SuperSpeed compared to control warm-up conditions (274.6 ± 42.5 versus 284.4 ± 43.7 ms). The effect of SuperSpeed warm-up was trivial on all other swing parameters (**Table 6**).

3.2 X-factor parameters

X-factor parameters showed either non-significant or trivial differences between SuperSpeed and control warm-up conditions (**Table 7**).

3.3 Peak angular velocity parameters

There were *small* (ES 0.24 to 0.33), significant ($p < 0.001$), and likely (more than 75%) increases in peak angular velocities of the torso (18.2 ± 21.3 °/s), lead arm (36.0 ± 43.37 °/s), and club (66.0 ± 79.4 °/s) subsequent the SuperSpeed compared to the control warm-up. The effect of SuperSpeed warm-up on the peak angular velocity of the pelvis and all timings of peak angular velocities was trivial (**Table 8)**.

3.4 Centre of mass parameters

SuperSpeed warm-up had a *small* (ES 0.24), significant ($p < 0.001$), and likely (more than 75%) effect on the COM position at the top of the backswing in the X-direction, indicating that the COM was closer to the target on average by 0.59 ± 0.92 cm (**Table 9**). At impact, the COM was more posterior (i.e., to the left of the target line) subsequent the SuperSpeed warm-up (-0.34 ± 0.41 cm, ES -0.32, $p < 0.001$, more than 75% likely) based on its Y position. A *small* significant ($p < 0.001$) change in X position at impact (0.54 ± 1.08 cm) was also noted, but the likelihood of the effect was less than 75%. All other changes in COM parameters between warm-up conditions were not meaningful (**Table 9**).

Table 6. Swing parameters (mean ± standard deviation) with control and SuperSpeed warm-up protocols in high level amateur golfers (*n* = 12). Effect of SuperSpeed warm-up expressed using change in mean, effect size [95% confidence limits], magnitude-based inference, and paired *t*-test *p*-value statistics.

Parameters	Control	Super Speed ^{a}	Change	ES [LL, UL]	MBI	*p*-value
CHS$_{peak}$ (mph)	100.2 ± 9.7	102.8 ± 10.09	2.58 ± 3.13	0.26 [0.18, 0.35]	Small§	< 0.001*
CHS$_{impact}$ (mph)	100.0 ± 9.7	102.5 ± 10.36	2.39 ± 3.55	0.24 [0.15, 0.34]	Small§	< 0.001*
CHS$_{peak}$ to CHS$_{impact}$ (ms)	-1.4 ± 1.5	-1.13 ± 1.74	0.30 ± 2.01	0.19 [-0.14, 0.53]	Trivial	0.253
Ball$_{peak\_R}$ (m/s)	63.3 ± 6.4	63. 6 ± 7.7	0.26 ± 3.47	0.04[-0.10, 0.18]	Trivial§	0.576
Ball$_{peak\_X}$ (m/s)	61.8 ± 6.1	62.0 ± 7.6	0.19 ± 3.68	0.03 [-0.13, 0.19]	Trivial§	0.694
Ball$_{peak\_Y}$ (m/s)	0.2 ± 3.1	0.5 ± 3.1	0.28 ± 2.96	0.09 [-0.16, 0.34]	Trivial§	0.472
Ball$_{peak\_Z}$ (m/s)	12.9 ± 4.0	12.4 ± 6.0	-0.51 ± 5.46	-0.13 [-0.49, 0.23]	Trivial	0.480
Smash factor^{a}	1.42 ± 0.04	1.39 ± 0.08	-0.03 ± 0.08	-0.80 [-1.41, -0.20]	Moderate	0.008*
Backswing time (ms)	879.6 ± 101.4	859.51 ± 83.89	-20.11 ± 54.34	-0.20 [-0.34, -0.05]	Trivial	0.009*
Downswing time (ms)	284.4 ± 43.7	274.57 ± 42.45	-9.85 ± 9.04	-0.22 [-0.28, -0.17]	Small§	< 0.001*
Follow-through time (ms)	187.1 ± 25.1	184.53 ± 25.53	-2.56 ± 10.48	-0.10 [-0.21, 0.01]	Trivial§	0.070
Backswing ratio	3.1 ± 0.4	3.2 ± 0.5	0.1 ± 0.2	0.10 [-0.02, 0.22]	Trivial§	0.097
Follow-through ratio	0.7 ± 0.1	0.7 ± 0.1	0.00 ± 0.00	0.12 [0.03, 0.20]	Trivial§	0.010*

Notes. ^{a} Smash factor calculated as Ball$_{peak\_R}$/CHS$_{peak}$. Ball$_{peak\_R}$, Resultant peak ball speed; Ball$_{peak\_X}$ Target direction peak ball velocity; Ball$_{peak\_Y}$, Left/right peak ball velocity; Ball$_{peak\_Z}$, Superior-inferior peak ball velocity; CHS, Clubhead speed; ES, Effect size; LL, Lower confidence limit;; MBI, Magnitude-based inference; UL, Upper confidence limit §, Likelihood > 75%; Grey fill indicates a non-trivial, significant ($p < 0.05$), and likely (> 75% likely) effect; *, p-value < 0.05.

Table 7. X-factor parameters (mean ± standard deviation) with control and SuperSpeed warm-up protocols in high level amateur golfers ($n = 12$). Effect of SuperSpeed warm-up expressed using change in mean, effect size [95% confidence limits], magnitude-based inference, and paired t-test p-value statistics.

Parameters	Control	Super Speed	Change	ES [LL, UL]	MBI	p-value
X-factor at impact (°)	-31.51 ± 7.59	-31.34 ± 8.61	0.17 ± 6.22	0.02 [-0.19, 0.24]	Trivial§	0.842
X-factor peak (°)	-61.70 ± 8.81	-62.47 ± 10.98	-0.78 ± 4.05	-0.09 [-0.21, 0.04]	Trivial§	0.169
X-factor at top (°)	-57.84 ± 8.97	-59.03 ± 10.85	-1.19 ± 4.11	-0.13 [-0.26, -0.01]	Trivial§	0.039*
X-factor peak-impact (°)	-30.30 ± 8.31	-30.31 ± 8.58	-0.01 ± 7.01	0.00 [-0.23, 0.23]	Trivial§	0.994
X-factor stretch (°)	-3.93 ± 3.92	-3.51 ± 4.12	0.43 ± 1.16	0.11 [0.03, 0.19]	Trivial§	0.011*
X-factor top-impact (°)	-23.51 ± 9.97	-26.86 ± 10.57	-0.43 ± 7.56	-0.04 [-0.25, 0.16]	Trivial§	0.683
X-factor time peak-impact (ms)	-21.45 ± 4.45	-21.35 ± 4.16	0.10 ± 2.29	0.02 [-0.12, 0.16]	Trivial§	0.756
X-factor time max-top (ms)	7.15 ± 6.96	6.22 ± 6.26	-0.93 ± 2.29	-0.13 [-0.22, -0.04]	Trivial§	0.005*

Notes. ES, Effect size; LL, Lower confidence limit; MBI, Magnitude-based inference; UL, Upper confidence limit; §, Likelihood > 75%; Grey fill indicates a non-trivial, significant ($p < 0.05$), and likely (> 75% likely) effect; *, p-value < 0.05.

Table 8. Peak angular velocity parameters (mean ± standard deviation) with control and SuperSpeed warm-up protocols in high level amateur golfers ($n = 12$). Effect of SuperSpeed warm-up expressed using change in mean, effect size [95% confidence limits], magnitude-based inference, and paired t-test p-value statistics.

Parameters	Control	SuperSpeed	Change	ES [LL, UL]	MBI	p-value
Pelvis (°/s)	447.5 ± 76.2	460.7 ± 88.06	13.3 ± 25.41	0.17 [0.08, 0.26]	Trivial	< 0.001*
Torso (°/s)	700.5 ± 73.5	718.6 ± 81.7	18.2 ± 21.3	0.24 [0.16, 0.32]	Small§	< 0.001*
Lead arm (°/s)	1053.8 ± 107.9	1089.8 ± 111.0	36.0 ± 43.7	0.33 [0.22, 0.44]	Small§	< 0.001*
Club (°/s)	2142.9 ± 200.6	2208.9 ± 205.7	66.0 ± 79.4	0.32 [0.22, 0.43]	Small§	< 0.001*
Time before impact pelvis (ms)	121.2 ± 23.6	119.6 ± 21.6	-1.62 ± 11.26	-0.07 [-0.20, 0.06]	Trivial§	0.299
Time before impact torso (ms)	85.7 ± 20.3	86.9 ± 17.7	1.17 ± 7.82	0.06 [-0.05, 0.16]	Trivial§	0.281
Time before impact lead arm (ms)	82.0 ± 22.6	84.2 ± 21.1	2.23 ± 7.84	0.10 [0.00, 0.19]	Trivial§	0.044*
Time before impact club (ms)	3.53 ± 2.18	3.40 ± 2.91	-0.14 ± 3.19	-0.06 [-0.51, 0.38]	Trivial	0.776

Notes. ES, Effect size; LL, Lower confidence limit; MBI, Magnitude-based inference; UL, Upper confidence limit; §, Likelihood > 75%; Grey fill indicates a non-trivial, significant ($p < 0.05$), and likely (> 75% likely) effect; *, p-value < 0.05.

Table 9. Centre of mass (COM) (mean ± standard deviation) with control and SuperSpeed warm-up protocols in high level amateur (*n* = 12). Effect of SuperSpeed warm-up expressed using change in mean, effect size [95% confidence limits], magnitude-based inference, and paired *t*-test *p*-value statistics.

Parameters	**Control**	**Super Speed**	**Change**	**ES [LL, UL]**	**MBI**	***p*-value**
COM at impact X (cm)	4.92 ± 2.45	5.46 ± 02.59	0.54 ± 1.08	0.22 [0.10, 0.34]	Small	0.001*
COM at impact Y (cm)	-0.08 ± 2.20	-0.22 ± 1.89	-0.14 ± 1.14	-0.06 [-0.21, 0.08]	Trivial§	0.371
COM at impact Z (cm)	4.05 ± 1.65	4.23 ± 1.70	0.18 ± 0.67	0.11 [0.00, 0.22]	Trivial§	0.059
COM at top X (cm)	-5.76 ± 2.41	-5.17 ± 2.40	0.59 ± 0.92	0.24 [0.14, 0.34]	Small§	< 0.001*
COM at top Y (cm)	1.37 ± 1.95	1.68 ± 1.74	0.31 ± 0.90	0.16 [0.03, 0.28]	Trivial§	0.015*
COM at top Z (cm)	1.49 ± 1.72	01.21 ± 1.63	-0.29 ± 0.58	-0.16 [-0.26, -0.07]	Trivial§	0.001*
COM at top-minimum X (cm)	-6.06 ± 2.76	-5.89 ± 2.60	0.16 ± 0.62	0.06 [0.00, 0.00]	Trivial§	0.060
COM at top-minimum Y (cm)	-0.69 ± 0.86	-0.55 ± 0.94	0.14 ± 0.34	0.16 [0.00, 0.00]	Trivial§	0.005
COM at top-minimum Z (cm)	1.97 ± 1.15	1.90 ± 0.91	-0.07 ± 0.47	-0.06 [0.00, 0.00]	Trivial§	0.275
COM at impact-minimum X (cm)	4.32 ± 2.52	4.48 ± 2.58	0.17 ± 1.06	0.06 [0.00, 0.00]	Trivial§	0.267
COM at impact-minimum Y (cm)	-2.14 ± 1.03	-2.48 ± 1.04	-0.34 ± 0.41	-0.32 [0.00, 0.00]	Small§	< 0.001*
COM at impact-minimum Z (cm)	4.48 ± 2.08	4.86 ± 2.26	0.38 ± 0.61	0.18 [0.00, 0.01]	Trivial	< 0.001*
COM at minimum vertical position X (cm)	0.30 ± 3.73	0.72 ± 3.74	0.42 ± 0.89	0.11 [0.05, 0.18]	Trivial§	0.001*
COM at minimum vertical position Y (cm)	2.06 ± 2.11	2.23 ± 1.85	0.17 ± 0.96	0.08 [-0.04, 0.20]	Trivial§	0.194
COM at minimum vertical position Z (cm)	-0.48 ± 1.87	-0.70 ± 1.93	-0.22 ± 0.47	-0.11 [-0.18, -0.05]	Trivial§	0.001*
COM displacement velocity at impact X (cm/s)	10.05 ± 15.70	9.63 ± 13.31	-0.42 ± 5.33	-0.03 [-0.12, 0.07]	Trivial§	0.570
COM displacement velocity at impact Y (cm/s)	-3.80 ± 6.94	-4.73 ± 7.08	-0.94 ± 3.49	-0.13 [-0.27, 0.01]	Trivial§	0.059
COM displacement velocity at impact Z (cm/s)	26.37 ± 16.89	25.92 ± 17.28	-0.45 ± 6.90	-0.03 [-0.14, 0.09]	Trivial§	0.637

Notes. COM, Centre of mass; ES, Effect size; LL, Lower confidence limit; MBI, Magnitude-based inference; UL, Upper confidence limit; X, Target direction ; Y, Left/right of virtual laboratory set up; Z, Superior/inferior; §, Likelihood > 75%; Grey fill indicates a non-trivial, significant ($p < 0.05$), and likely (> 75% likely) effect; *, p-value < 0.05.

Discussion

With increasing monetary incentives in golf, players are trialling various warm-up methods to enhance performance. Recently, professional golfers have been endorsing SuperSpeed Golf^{TM} products, which claim to enhance performance by increasing clubhead speed. In the current study, incorporating SuperSpeed weighted clubs in a warm-up led to significant and meaningful improvements in clubhead speed by 2.6 mph (**Table 6**). From a biomechanical perspective, these improvements were associated with a quicker downswing time; increased peak torso, lead arm, and club angular velocities; and COM position closer to the target direction at the top of backswing and further away from the tee in the posterior direction at impact. These changes, however, did not lead to significant or meaningful improvements in ball speeds and resulted in a significant meaningful negative effect on smash factor (**Table 6**), suggesting that the increased clubhead speed was not efficiently transferred to the ball at impact.

The lack of transference of the increased clubhead speed to the ball with SuperSpeed warm-up suggests that the centeredness of strike might have been affected[174,200,201]. The variability, distance, and accuracy of golf swings have shown strong correlation to scoring and tournament ranking[4,15,18]. To maximise distance, the clubface needs to strike the ball in line with the centre of mass of the club, known as centeredness[174,201,202]. Individuals with increased skill and physical ability are able to control golf club delivery and the centre of the strike better, influencing the resultant launch conditions of the golf ball[174,203]. For this reason, we recruited high-calibre golfers with a handicap of less than 3.0 to ensure quality of strike. Most participants (i.e., 75%) reported no previous experience using SuperSpeed clubs. The changes in biomechanical patterning – albeit few and small – and increase in clubhead speed subsequent the SuperSpeed warm-up was most likely unfamiliar to participants. The transfer of clubhead speed to ball speed (otherwise known as smash factor[40]) was 1.42 after the control warm-up and decreased to 1.39 following the SuperSpeed warm-up. If the smash factor of 1.42 was maintained after the SuperSpeed warm up, ball speed would have increased by 3.25 mph, equating to an increased carry distance of 5.5 metres[40]. Therefore, integrating the use of SuperSpeed clubs more regularly in training and competition to increase exposure and experience to the protocol might lead to a greater transference of the observed increase in clubhead speed to the ball, and ultimately driving distance and performance[150].

The changes in clubhead speed observed with the SuperSpeed club warm-up were associated with changes in other biomechanical measures, although probably not as many as anticipated. For instance, no changes in X-factor parameters were noted in our study albeit changes in downswing time and clubhead speed. Across the literature, various levels of association between X-factor measures and clubhead speed are reported[29,30,34,35,38,42,44,46,53,61,70]. The variability in X-factor computational methods has been cited as one of the main reason for the inconsistent findings in relation to X-factor and golf swing performance[70], which might explain our results. The fact that SuperSpeed warm-up had no effect on driving performance (i.e., ball speed) could also contribute to the lack of change in X-factor.

The increase in clubhead speed resulted from small significant increases in the peak angular velocities of the torso, lead arm, and club, with no change in the time to peak velocities in relation to impact. To achieve maximal velocity, a golfer relies on the kinetic chain principle, which is the transfer of energy and momentum through sequential body segments to achieve the greatest magnitude in the most distal segment[32,33]. Previous research has demonstrated that small changes in sequence timing (10 ms) can result in significant alterations to the distal segment velocity (club) by as much as 6.2 mph[204]. Findings in this research suggest that our participants maintained their proximal to distal sequencing patterns after the SuperSpeed warm-up compared to the control whilst still increasing segmental and club angular velocities (**Table 8**). It is possible that the increased angular velocities noted resulting from the SuperSpeed warm-up protocol were from enhanced myosin regulatory light chains phosphorylation and/or increased neural excitability through PAP[117,179].

A *small* significant change was also seen in select COM parameters during the golf swing. After the SuperSpeed intervention, participants decreased the amount of shift away from the target during the backswing, in line with the increased and earlier body weight transfer to the lead foot during downswing seen in superior skilled players[74] and has been linked to increased clubhead speed on an individual basis[205,206]. To limit potential bias in our data, warm-up conditions were randomised and a single investigator applied 3D markers across all testing sessions. The intraclass correlation coefficient between sessions for 3D motion data range from 0.931 to 0.999 for the pelvis in the sagittal, coronal, and transverse planes[207], suggesting good within researcher between session reliability. As such, we deem that the changes observed here in the biomechanical data reflect actual changes in performance. For instance, the 0.59 cm change in pelvis position at the top of the backswing would be clinically meaningful for our high-level golfers.

Previous sport science research on PAP and overspeed training methods via weighted equipment during swinging motions has focused on baseball, with no significant increases in bat velocity found[85,143-148]. The majority of the equipment used within these baseball studies (i.e., 93%) was more than 10% heavier or lighter than standard bat mass, which has been shown to alter batting biomechanics[145,148]. Similarly in golf, increased clubhead mass by 4 to 7% is reported to negatively impact clubhead speed in golfers with a handicap < 5.0[174]. That said, DeRenne et al.[148] reported that using a 3.3% lighter than standard baseball bat during a warm-up resulted in the highest subsequent batting speed at 27.1 m/s, although this speed was not significantly greater than the 26.5 m/s speed subsequent a standard bat warm-up (difference of 2.3% in speed). These authors' results align with our SuperSpeed weighted-club warm-up resulting in increasing clubhead speeds by 2.59% compared to a control warm-up. That said, the SuperSpeed protocol warrants further study, as it currently combines the use of both lighter and heavier than standard clubs in a somewhat arbitrary sequence. As such, the resulting increase in clubhead speed is suggested to stem from both PAP and overspeed mechanisms, with one mechanism potentially being detrimental to the other. PAP mechanisms have previously been shown to increase clubhead speed in golf via CMJs[186], suggested to result from an increased synchronisation of the body segments to enhance force from the ground up. Ground reaction forces were not collected as part of the current study; hence, we are unable to confirm this speculation. However, the *small* changes in COM position and increases in angular velocities at the torso, lead arm, and club segments support maintenance (or improvement) in synchronisation of body segments. From a thermoregulatory perspective, the SuperSpeed warm-up protocol might have increased muscle temperature more than the control warm-up protocol, which has been advanced as reasons for enhanced performance in other PAP-inducing studies[114,186]. In support, elevated muscle temperature has been correlated to increased performance in sports[98-100]. More mechanistic investigations are needed to confirm the underlying mechanisms leading to enhanced clubhead speed following the SuperSpeed warm-up.

One limitation of this study is the 120 seconds transition time between the SuperSpeed warm-up protocol and testing trials. Previous research using heavy resistance exercises to induce PAP reports the greatest enhancements in performance from transition times ranging between 4 to 12 minutes[127,141,151]. The SuperSpeed warm-up protocol does not require the same intensity as resistance exercises typically used to induce PAP (i.e., 70% one repetition max or above). Therefore, the time for fatigue to dissipate and potentiation to enhance performance is likely to occur sooner with weighted equipment given the lighter relative loads, which would align with research demonstrating improvements in performance after plyometric exercises with short transition times (i.e., 30 s)[208]. Another limitation of this study is the laboratory environment, as highlighted within golf warm-up literature[76]. The laboratory environment is not a true representation of the demands placed on an individual during practice or tournament play[183,209], which could affect our results. The use of a net, for instance, limits the ability of players to focus on a target. Participants in this study were directed to hit a ball covered in reflective tape into the middle of the net placed 5.5 m away. The influence of the tape on ball speed and smash factor variables was not examined. Due to these limitation, information regarding club path and ball dispersion was not analysed as it was deemed inaccurate reflection of performance in relation to games demands.

Conclusion

The use of a SuperSpeed compared to a control warm-up protocol influenced COM and peak angular segmental velocities, which resulted in an increased clubhead speed. Despite previous research reporting X-factor variables as determinants to clubhead speed[30], no meaningful changes were seen in X-factor variables following the SuperSpeed warm-up, which might be because ball speed remained unaffected. The lack of transference between the enhanced clubhead speed from the SuperSpeed warm-up protocol to ball speed is likely due to the lack of familiarity with the changes in biomechanical golf swing patterning. Players with increased experience with the SuperSpeed warm-up or increased skill level may have been better able to use the increase clubhead speed in an effective manner. Future research investigating the persistence of the effects observed subsequent the SuperSpeed warm-up protocol is needed to better understand the practical value of the increase in clubhead speed and how to best implement the protocol in practice.

Chapter Four: Experimental Study – Effects of a Weighted Club Warm-Up on Golf Performance and Biomechanics Across Sets

Abstract

Introduction:

Competitive golfers are using various warm-up strategies to enhance clubhead speed given the strong association between driving distance and tournament performance. Our aims were to investigate the persistence of the effect of the SuperSpeed Golf™ weighted club warm-up protocol on clubhead, ball, and swing biomechanics.

Methods:

Twelve competitive golfers (handicap < 3.0) completed five sets of five swings walking 400 m between sets under two randomised warm-up conditions (control and SuperSpeed). Swing, peak angular velocity, and centre of mass (COM) parameters collected using 3D motion capture (500 Hz) were compared between warm-up conditions using Cohen's standardised effect size (ES). Any meaningful, likely, and significant ES detected in the initial set (acute effect) was reassessed for persistence regularity in the subsequent sets.

Results:

SuperSpeed warm-up led to significant ($p < 0.05$) *small* (ES > 0.2) and likely (greater than 75% likelihood) changes in clubhead speed (2.6 mph); peak angular velocity of the torso, lead arm, and club; and two COM variables compared to the control warm-up in the initial set. No significant change was seen in ball speed in the initial set, resulting in a *moderate* negative change in the smash factor (ES -0.80, $p = 0.008$). All changes observed in the initial set of five swings were no longer meaningful in the subsequent sets.

Conclusion:

The SuperSpeed warm-up protocol significantly and meaningfully increased clubhead speed and influenced a subset of swing biomechanical variables acutely. However, these changes were no longer meaningful after walking the distance of a simulated golf hole. Our findings suggest that the SuperSpeed warm-up protocol performed pre-tournament does not meaningfully improve golfing performance in a golf-specific context from the second hole onwards.

Introduction

The long game in golf explains over two-thirds of the difference in scores between Professional Golfers Association (PGA) Tour competitors[14], with clubhead speed being the main variable associated with long game and golfing performance[24,47,48,173,174]. In the 2018 PGA Tour season, 60 players averaged over 115.8 mph in clubhead speed, with 87% of these players earning enough money to maintain their professional status the following year[3,39]. Given the importance of clubhead speed on golfing performance and tournament outcomes; players, coaches, and researchers are continuously seeking to better understand golf swing mechanics and ways to enhance clubhead speed[16,26,29,30,36-38].

One avenue for improving performance in golf is through warm-up strategies[68]. Competitive golfers are using various warm-up methods prior to tournaments to enhance clubhead speed. SuperSpeed Golf™ (Chicago, IL) has designed a set of weighted golf clubs (SuperSpeed Golf Training System) and associated warm-up protocol aimed at enhancing clubhead speed and swing performance[178]. SuperSpeed Golf™ currently claims to have over 600 professional golfers on tour using their product[187], with high profile players such as Phil Mickelson seen using the weighted clubs as part of his warm-up prior to the 2018 US Open tournament[188]. This prompted our team to investigate the effect of the SuperSpeed warm-up protocol on driving performance and biomechanics, finding that the protocol significantly increased clubhead speed (2.6 mph) and changed select biomechanical variables when compared to a control warm-up condition in 12 competitive golfers. Although the enhancements in clubhead speed did not transfer to an increase in ball speed, the findings indicate changes in golf swing mechanics and potential for improved performance via the SuperSpeed weighted golf clubs and warm-up protocol that warrant further investigation.

A number of ball striking sports other than golf, including baseball[85,143-148], ice hockey[175], cricket[176], and tennis[177], have incorporated the use of weighted equipment as part of warm-up strategies to potentiate subsequent swing performance based on post activation potentiation (PAP) mechanisms. PAP induces an increase in performance when the net balance between potentiation and fatigue favours potentiation in recently activated muscle[113-118]. The resulting increase in performance is due to elevation in myosin regulatory light chains (RLC) phosphorylation[179] and neural excitability[117,119]. In sports, PAP is generally induced using resistance exercises that elicit a similar biomechanical movement pattern to the activity requirements[118,127,135,140-142,180]. The use of SuperSpeed clubs is the closest equivalent of a PAP-inducing activity replicating the sport-specific demands of golf. However, the effects of PAP depend on a number of factors, including transition times[127,141,151-154], the specific PAP-inducing exercise used[127,135,140,151], and the resistance training experience[140,151,152] and strength levels[210,211] of individuals.

Increases in power production following PAP-inducing exercises have been seen with transition times ranging from 2 to 18.5 minutes[140,150], with 4 to 12 minutes maximising the potentiation effect in high-level athletes[127,135,141,151-155]. The PAP-inducing exercise load influences the transition times needed to potentiate subsequent performance due to the increased twitch response and levels of fatigue accumulated from heavier loads[123,125,132-135]. Research using heavy back squats, upwards of 90% 1-repetition maximum (1RM) as PAP stimulus indicates that more than 4 minutes of transition is required to increase subsequent sprinting[123,125,135] and jumping[127,141,154,210] performance. To complicate the practical application of PAP further, different heavy-loaded PAP-inducing exercises have been shown to potentiate subsequent performances with various transition times. For instance, Hex bar deadlifts increased vertical jump performance at 2 to 6 minutes post PAP inducing stimulus[141], while power cleans enhanced 20 m sprint times 7 to 10 minutes post stimulus[135]. Plyometric exercises have also been used to induce PAP with the required transition times needed for fatigue to dissipate and potentiation to remain being relatively short in comparison (i.e., less than 2 minutes)[137,186,208] to heavy resistance exercises[117]. Our previous research on the acute effects of a SuperSpeed club warm-up indicates potentiated clubhead speeds using relatively short transition times (90 s), aligning with research using more plyometric-based exercises for potentiation.

Ball striking sports have used not only heavier, but also lighter than standard striking implements during a warm-up to enhance performance based on overspeed principles. Overspeed training involves the use of an external stimulus to exceed unassisted maximal velocities of a specific sporting task[162]. Overspeed training is commonly applied in sprinting with the incorporation of downhill[163,164,181] or band-assisted[165] running. Positive enhancements in sprinting times with overspeed training have been observed[126,165] and are linked to the supramaximal muscle requirements needed to perform the velocity-enhanced movements resulting from an overspeed stimulus[163,165,181,212,213]. The SuperSpeed Golf™ warm-up protocol incorporates the use of two clubs that are lighter than standard, and one club that is heavier than standard[178] suggesting that potentiation might result from both overspeed and PAP mechanisms. Although the potentiation mechanisms with overspeed are similar to those of PAP, research on the persistence of the potentiation effect resulting from an overspeed stimulus is scarce.

SuperSpeed Golf™ claims that performance enhancements subsequent the SuperSpeed warm-up protocol can last up to 30 minutes, which contradicts PAP research that indicates no significant improvements in performance past 18.5 minutes[150]. In a golf setting, 13 minutes would reflect the duration of playing one hole. Therefore, our aim was to investigate the persistence of the potentiation effect of the SuperSpeed warm-up protocol on driving performance and biomechanics using a simulated golf tournament scenario in a cohort of high level amateur golfers. It was hypothesised that the enhancements seen in clubhead speed from our previous research would persist for the duration of at least two simulated holes.

Methods

2.1 Participants

Sample size requirements were calculated from standard two-tailed hypothesis equations[189], an 80% power ($\beta = 0.20$), 5% significance level ($\alpha = 0.05$), critical values of the *t*-distribution, and test-retest reliability data on clubhead speed from previous studies[28,190]. These calculations indicated that 7 to 11 participants were needed to identify reported minimal detectable mean changes (3.7 to 6.9 mph) in clubhead speeds with corresponding standard deviations (3.1 to 4.6 mph) at the 5% significance level with 80% power. To account for potential withdrawals or missing data, 12 participants were targeted.

Twelve competitive golfers (7 males, 5 females) volunteered to participate (**Table 10**) and completed the experiment. All participants were right-hand dominant; hence, for all participants, the lead arm and hip refer to the left-hand side of the body, and the trail arm and hip refer to the right-hand side. The inclusion criteria were: minimum of 16 years of age, free from any injuries, were actively involved in, and had at least one year of resistance training experience, and registered with a New Zealand golf handicap of less than 3.0 (due to high skilled amateur golfers having a reduced level of movement variability[32]). Participants were excluded if not meeting these inclusion criteria. Participants were recruited via electronic emails sent to current representative players of the following associations: Bay of Plenty Golf, Waikato Golf, and New Zealand Golf. All participants were informed about the potential risks and benefits of study participation and were required to provide written informed consent. The testing protocol was approved by the Human Research Ethics Committee of the University of Waikato [HREC (Health) #2018-35], followed international ethical standards[191], and adhered to the Declaration of Helsinki.

Table 10. Participant characteristics (mean ± standard deviation).

Characteristic	**Male (*n* = 7)**	**Female (*n* = 5)**	**Total (*n* = 12)**
Height (cm)	8 ± 8	166 ± 7	174 ± 10
Body mass (kg)	77.9 ± 18.2	64.9 ± 8.6	72.5 ± 15.8
Age (y)	23.7 ± 8.3	19.6 ± 3.8	22 ± 6.9
Current golf handicap	0.4 ± 1.8	1.0 ± 2.0	0.6 ± 1.8
Experience (y)	13.4 ± 8.1	9 ± 5.9	11.5 ± 7.3
Time spent playing golf (h/week)	15.4 ± 15.3	16.5 ± 7.3	15.9 ± 12.2

Notes. All participants were right-hand dominant.

Prior to the first testing session, participants completed a baseline questionnaire on golf experience, practice routines and anthropometric characteristics were recorded.

Participants also rated their prior experience with SuperSpeed clubs as none (*n* = 9), low (*n* = 2), moderate (*n* = 1), and high (*n* = 0).

2.2 Experimental protocol

A one-group within-subject repeated measures cohort study design was used to investigate the effect of warm-up condition (control versus SuperSpeed) on golf swing performance and biomechanics, with participants randomly assigned an order to complete the two conditions. Each warm-up condition was completed on two different days, at a similar time of day, within a 10-day period. Each participant was familiarised with the testing procedure before experimentation. Participants performed all golf swing testing trials using their own golf shoes and drivers. To investigate the persistence of any acute potentiation effect of the SuperSpeed warm-up condition, participants were required to complete five sets of five swings, walking 400 m between swing sets to simulate a golf tournament scenario.

The control warm-up was designed to replicate the habitual warm-up routine that players would perform in preparation to tournament play (**Figure 7**). The control warm-up required participants to swing their own clubs in progression of sand wedge, 9-iron, 6-iron, 3-iron (or 4-iron), and driver a total of five times each on their dominant side with a 30 s rest between clubs. The SuperSpeed warm-up (**Figure 7**) followed the manufacturer's recommendations and used the SuperSpeed clubs (**Figure 8**). The SuperSpeed clubs used during the warm-up are different for males and females (**Figure 8**); however, the protocol remains the same with participants progressing intensity, load, and velocity throughout the warm-up (**Figure 7**). The male SuperSpeed clubs were 23.53% lighter (light club), 8.62% lighter (medium club) and 9.24% heavier (heavy club) than the typical driver weight, 315 grams[192].

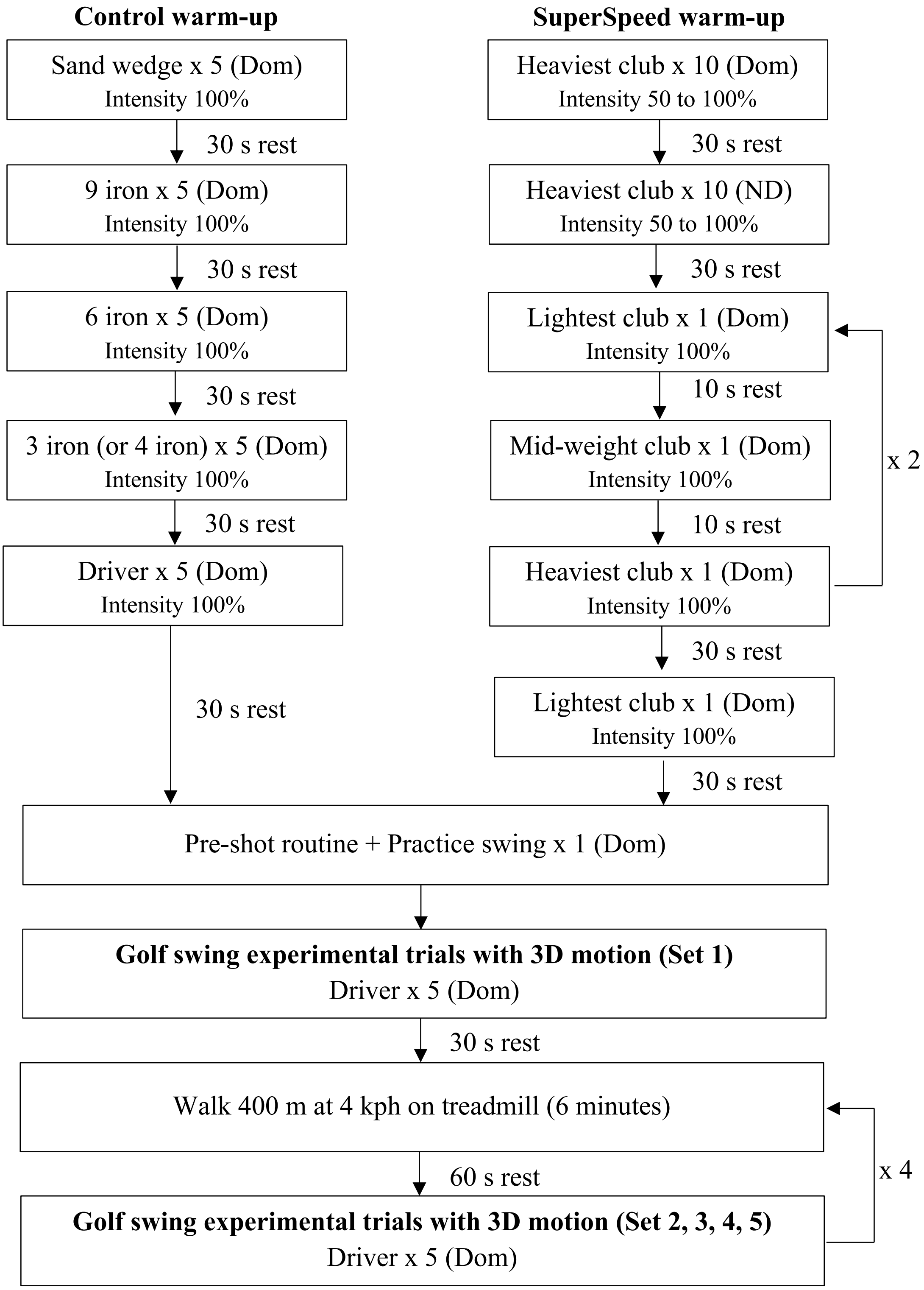

Figure 7. Flow diagram of control and SuperSpeed warm-up protocols for a right-hand dominant golfer. Dom, dominant: represents right-hand swings; ND, non-dominant: represents left-hand swings.

Club		Mass (g)		Protocol	
Name	**Colour**	**Stated[a]**	**Actual[b]**	**Male**	**Female**
Super light	Yellow	225.0	233.7		✓
Light	Green	255.0	261.9	✓	✓
Medium	Blue	290.0	297.6	✓	✓
Heavy	Red	335.0	341.0	✓	

Note. All clubs are 114.3 cm in length.
[a]Mass stated by the manufacturer SuperSpeed Golf^{TM} (Chicago, IL).
[b]Mass measure using Precisa XT6200C Instrument Ltd., Switzerland.

Figure 8. SuperSpeed clubs, characteristics, and protocol for males and females.

After the completion of the designated warm-up, participants completed their normal pre-shot routine, followed by swinging their own driver once. The researcher was thereby able to recognise players pre-shot routines and determine when to start the 3D motion capture system. After a 90 s rest period, the data collection trials began. Each participant was instructed to complete their normal pre-shot routine prior to each recorded trial and hit the golf ball "as far as possible" into the middle of the driving net using their natural golf swing. Participants would complete the five trials at a rate of one swing every 30 to 60 s depending on the duration of their pre-shot routine.

After the first set of five recorded trials, participants rested for 30 s and then walked on a treadmill (Steelflex PT10 Treadmill, Steelflex Fitness, Taiwan) for 400 m at a pace of 4 kph (6 minutes) to replicate the length, speed, and time a typical golfer would take to walk between teeing grounds on a golf course[214-218]. Golfers walk on average 7.89 to 8.25 km per round[214-216] (~438 to 458 m per hole), with the Royal and Ancient (R&A) rules of golf allowing 13 minutes to complete a par 4 hole[218]. Participants rested 60 s after the 400 m walk before completing one pre-shot routine and the subsequent set of five swings. Hence, the time from the end of the first set to the start of the second set was 7.5 minutes (rest 30 s, walk 6 minutes, rest 60 s). This process was repeated until 25 trials were completed (i.e., five sets of five swings).

2.3 Data collection

Testing was completed in a laboratory environment using a driving mat, with participants hitting towards a net placed 5.5 metres away from the tee (**Figure 9**). Participants used their own driver and new 2018 Titleist Pro V1 golf balls covered in reflective tape. Kinematic data were collected using the Qualisys Track Manager version 2.17 (build 4000), Golf Performance Visual3D Project Automated Framework version 4.0.1+66, one video camera (Oqus 210c) capturing at 50 Hz, and 10 infrared motion capture cameras (8 Oqus 700+, 2 Oqus 310+, Qualisys AB, Gothenburg, Sweden) capturing at 500 Hz. Prior to each session, the capture volume was calibrated using a 601.5 mm calibration wand and an L-frame that defined the Cartesian origin of the laboratory. The X-axis of the virtual laboratory was aligned with the target direction (+ towards target), Y-axis was perpendicular to the target direction (+ to the right of the target), and Z-axis was aligned with vertical (+ superior). From an initial golf-swing set-up position for all of our right-hand dominant participants, movements towards the target in the X-direction represented movements towards the lead (+ left) side, and movements towards the right of the target in the Y-direction represented movements towards the tee (+ forward). Each participant stood in the middle of the calibrated volume for 1 s to allow static calibration and case-specific model definition prior to the warm-up protocols. The local coordinates of all segments were derived from this static measurement.

Fifty-six 12.5 mm in diameter retro-reflective markers were affixed to participants (*n* = 50 makers) and the club (*n* = 6 markers) using Tesa® 4965 double-sided tape, Fixomull® stretch adhesive non-woven fabric, and Mastisol® liquid adhesive following guidelines from the Golf Performance Visual3D Project Automated Framework (**Figure 9**). The golf ball was also covered in reflective tape to track the ball. Markers were placed on participants on the following locations: front, left, and right head; bilateral acromial edges, posterior and anterior upper arms, humeral lateral epicondyles, radial styloid processes, and ulnar styloid processes; leading forearm, supra wrist, and 3rd metacarpal head; bilateral supra (7th cervical region) and infra (4th thoracic region) upper back; bilateral iliac crests, anterior superior iliac spines, posterior superior iliac spine, and infra posterior superior iliac spines;

bilateral posterior and anterior thighs, femoral lateral and medial epicondyles, tibial tuberosities, lateral and medial malleoli, calcanei, and 5th and 2nd metatarsal heads. For the club, four markers were spaced 5 cm apart on the shaft starting 5 cm below the grip, with markers also attached to the heel and toe of the clubface. Markers on the lead arm ulnar styloid process, iliac crests, anterior superior iliac spines, and clubface were removed once the static trial was completed.

Figure 9. Participant in static position with full marker set prior to completing a warm-up condition with graphical representation of the virtual lab direction.

From the marker set, a 14-segment biomechanical model with 6 degrees of freedom at each joint was constructed in Visual3D Professional™ Software version 6.01.36 (C-Motion, Germantown, MD) to model participants. Segments included the head, upper arms, lower arms, lead hand, torso pelvis, thighs, shanks, and feet, from which the centre of mass (COM) of individuals was derived based on mechanical principles and Dempster's regression equations[193]. The upper end of the torso was defined using the acromial edges and the lower end of the torso based on the iliac crest markers[194], and a CODA pelvis was used to define the hip joint centres[195]. In addition, three segments were constructed to define the clubface, clubhead, and ball.

2.4 Data processing

Marker data for all golf swing experimental trials were exported to the C3D format and processed in Visual3D Professional^{TM}. The swing was broken down into six time points: takeaway (clubhead velocity exceeds 0.1 mph), half back (lead arm is horizontal), top of backswing (angular velocity of the club reaches zero), half down (lead arm is horizontal), impact (frame before clubhead passes ball position in the X-direction), and follow-through (clubhead reaches its maximum height after impact)[196]. Marker data were interpolated using a least-squares fit 3rd order polynomial, and filtered using a 4th order 6 Hz Butterworth bidirectional filter except for the lead arm and club markers. To account for discontinuities in marker trajectories at impact, post-impact samples were replaced by a linear extrapolation of the clubhead path to avoid endpoint artefact[197]. The downswing phase data were subsequently filtered at 10 Hz, follow-through at 25 Hz, and backswing at 10 Hz. For the purpose of this study, only the downswing phase (from top of backswing to impact) was of interest.

Kinematic parameters were calculated using rigid-body analysis and Euler angles obtained from the static calibration. Body angles in the sagittal (flexion–extension), coronal (adduction–abduction), and transverse (internal–external rotation) planes were calculated using an *x-y-z* Cardan sequence equivalent to the Joint Coordinate System. Pelvis and torso angles in the sagittal (anterior–posterior and flexion–extension), coronal (lead, left and trial, right side), and transverse (dominant, non–dominant rotation) planes were defined relative to the laboratory using an *z-y-x* Cardan sequence based on work from Baker[198]. X-factor angles were also calculated using an *z-y-x* Cardan sequence, and defined the separation of the torso in relation to the pelvis around the Z-axis[70]. A negative angle indicated the torso rotated away from that target in relation to the pelvis during the backswing or the pelvis leading the torso (rotated towards the target) during the downswing.

2.5 Parameters

Swing, X-factor, angular velocity, and COM parameters were of primary interest based on biomechanical literature on golf[17,29,30,34-38,41-44,46,53-61,70]. More specifically, swing variables of interest included: clubhead peak speed during downswing (CHS_{peak}, mph); clubhead impact speed (CHS_{impact}, mph); time between CHS_{peak} and CHS_{impact} (ms); resultant ($Ball_{peak\_R}$), anterior-posterior ($Ball_{peak\_X}$), medial-lateral ($Ball_{peak\_Y}$), and superior-inferior ($Ball_{peak\_Z}$) golf ball velocity (mph); smash factor ($Ball_{peak\_R}/CHS_{peak}$); backswing, downswing, and follow-through times (ms); and downswing (backswing time: downswing time) and follow-through (follow-through time: downswing time) ratios. X-factor variables extracted were: X-factor peak, at top of backswing, and at impact (°); difference between X-factor peak and impact (°), and X-factor peak and X-factor at top of backswing (X-factor stretch, °); and time between X-factor peak and impact, and X-factor peak and top of backswing (ms). Peak rotational angular velocities of the pelvis, torso, lead arm, and club (°/s), and timing of these peaks in relation to ball impact (ms) were also extracted. Finally, COM variables extracted from the data were: COM position at impact, at top of backswing, and at its lowest vertical position during the downswing phase in relation to position at takeaway in the laboratory *x*-*y*-*z* directions (cm); difference in COM position between impact and its lowest vertical position, and top of backswing and its lowest vertical position (cm); and COM linear displacement velocity at impact in the laboratory *x*-*y*-*z* directions (cm/s). Since participants were directed to hit the ball into the middle of the net placed 5.5 m away, information regarding club path and ball dispersion were not analysed as it was deemed inaccurate reflection of performance in relation to game demands.

2.6 Statistical analysis

Means and standard deviations (mean ± SD) were computed for all parameters. Changes in mean and standardised effect sizes (ES) were computed to compare the effect of warm-up condition on the parameters of interest. The ES was considered *small, moderate, large,* and *very large* when reaching absolute threshold values of 0.2, 0.6, 1.2, and 2.0, and trivial when < 0.20[199]. An effect was deemed 'clear' when it's 95% confidence limit (CL) did not overlap the thresholds for small positive and small negative effect (i.e., 5%), and 'likely' to be clinically meaningful when its probability exceeded 75%[199]. Paired *t*-tests were used to investigate differences between warm-up conditions with the threshold for statistical significance set at *p*

< 0.05. Only non-trivial, clear, likely, significant effects were deemed to reflect a meaningful biomechanical change.

To investigate the persistence of any potentiation effect while reducing the chance of Type I errors, the effect of warm-up condition on biomechanical parameters in Sets 2 to 5 was examined only for parameters exhibiting a meaningful change in Set 1 and key performance indicators (i.e., clubhead and resultant ball speed). Data were analysed using customised statistical spreadsheets (Microsoft Excel 2016, Microsoft Corp, Redmond WA, USA). Results were summarised using tables. Key figures of results are also provided as appendix (Appendix 2, Figures S5 – 7).

Results

3.1 Swing parameters

The SuperSpeed warm-up protocol induced a *small* (ES 0.26, 0.24, and -0.22) significant ($p < 0.001$) and likely (more than 75%) change in $CHS_{peak,}$ CHS_{impact}, and downswing time in Set 1, and *moderate* meaningful change in smash factor (ES -0.80, $p = 0.008$). From Set 2 onward, these effects became significantly trivial ($p < 0.003$), non-significant ($p > 0.05$), or less than 75% likely (**Table 11**), although the effect of warm-up on smash factor in Set 2 neared significance (ES -0.35, $p = 0.074$). The effect of warm-up condition on $Ball_{peak\_R}$ remained trivial throughout all five sets.

3.2 X-factor parameters

Given that X-factor parameters showed either non-significant or trivial differences between warm-up conditions in the first set, the persistence of the effect on X-factor parameters was not investigated.

3.3 Peak angular velocity parameters

The *small* (ES 0.24, 0.33, and 0.32) significant ($p < 0.001$) and likely (more than 75%) increases in peak angular velocities of the torso, lead arm, and club following the SuperSpeed warm-up condition seen in Set 1 were significantly trivial ($p <$

0.003), non-significant ($p > 0.05$), or unlikely (less than 75%) from the second set onwards (**Table 12**).

3.4 Centre of mass parameters

The SuperSpeed warm-up had a *small* (ES 0.24), significant ($p < 0.001$), and likely (more than 75%) effect on the COM position at the top of the swing in the X-direction acutely in Set 1, indicating that the COM was closer to the target. However, from Set 2 onwards, this effect was either less than 75% likely, non-significant, or trivial (**Table 13**). At impact, the COM was more posterior (i.e., to the left of the target line) based on its Y position following the SuperSpeed warm-up protocol (ES -0.32, $p < 0.001$, more than 75% likely) in both Set 1 and Set 3. However, the effect was non-significant, trivial, and unlikely in Set 2, Set 4, and Set 5 (**Table 13**).

Table 11. Swing parameters (mean ± standard deviation) with control and SuperSpeed warm-up protocols in high level amateur golfers (*n* = 12). Effect of SuperSpeed warm-up expressed using change in mean, effect size [95% confidence limits], magnitude-based inference, and paired *t*-test *p*-value statistics.

Set	Parameters	Control	SuperSpeed ^{a}	Change	ES [LL, UL]	MBI	*p*-value
1	CHS_{peak} (mph)	100.2 ± 9.7	102.8 ± 10.1	2.6 ± 3.1	0.26 [0.18, 0.35]	Small§	< 0.001*
2		100.0 ± 9.7	101.8 ± 9.7	1.8 ± 3.6	0.19 [0.08, 0.29]	Trivial	< 0.001*
3		99.4 ± 9.3	101.1 ± 9.1	1.8 ± 3.6	0.19 [0.09, 0.29]	Trivial	< 0.001*
4		100.0 ± 9.0	101.7 ± 9.2	1.7 ± 3.3	0.18 [0.08, 0.28]	Trivial	< 0.001*
5		101.0 ± 9.6	102.5 ± 8.7	1.5 ± 3.7	0.16 [0.05, 0.26]	Trivial§	0.003*
1	$\text{CHS}_{\text{impact}}$ (mph)	100.0 ± 9.7	102.5 ± 10.4	2.39 ± 3.6	0.24 [0.15, 0.34]	Small§	< 0.001*
2		99.7 ± 9.8	101.5 ± 9.7	1.8 ± 3.9	0.19 [0.08, 0.29]	Trivial§	< 0.001*
3		99.1 ± 9.5	100.8 ± 9.0	1.7 ± 3.7	0.17 [0.07, 0.28]	Trivial	< 0.001*
4		99.6 ± 9.5	101.4 ± 9.1	1.7 ± 3.7	0.18 [0.07, 0.28]	Trivial	< 0.001*
5		100.8 ± 9.7	102.3 ± 8.6	1.4 ± 3.9	0.15 [0.04, 0.25]	Trivial§	< 0.001*
1	$\text{Ball}_{\text{peak\_R}}$ (m/s)	63.3 ± 6.4	63.6 ± 7.7	0.26 ± 3.47	0.04 [-0.10, 0.18]	Trivial§	0.576
2		63.6 ± 5.7	64.0 ± 6.6	0.38 ± 2.18	0.07 [-0.04, 0.17]	Trivial§	0.199
3		62.5 ± 6.4	64.1 ± 6.0	1.55 ± 9.17	0.14 [-0.08, 0.37]	Trivial	0.208
4		63.4 ± 6.0	64.0 ± 6.2	0.67 ± 2.14	0.11 [0.02, 0.20]	Trivial§	0.021
5		64.0 ± 6.5	64.6 ± 6.2	0.62 ± 2.77	0.09 [-0.02, 0.21]	Trivial§	0.100
1	Smash factor^{a}	1.42 ± 0.04	1.39 ± 0.08	-0.03 ± 0.08	-0.80 [-1.41, -0.20]	Moderate§	0.008*
2		1.39 ± 0.08	1.37 ± 0.04	-0.01 ± 0.06	-0.35 [-0.73, -0.03]	Small§	0.074
3		1.44 ± 0.05	1.42 ± 0.06	-0.02 ± 0.07	-0.34 [-0.75, 0.07]	Small	0.104
4		1.42 ± 0.05	1.41 ± 0.05	-0.01 ± 0.06	-0.21 [0.51, 0.08]	Small	0.150
5		1.42 ± 0.08	1.41 ± 0.08	-0.01 ± 0.08	-0.10 [-0.35, 0.14]	Trivial§	0.414

Set	Parameters	Control	SuperSpeed [a]	Change	ES [LL, UL]	MBI	*p*-value
1	Downswing time (ms)	284.4 ± 43.7	274.6 ± 42.5	-9.85 ± 9.04	-0.22 [-0.28, -0.17]	Small§	< 0.001*
2		277.6 ± 41.1	269.0 ± 40.6	-8.64 ± 13.28	-0.21 [-0.29, -0.12]	Small	< 0.001*
3		277.6 ± 43.1	269.5 ± 40.8	-8.15 ± 10.68	-0.19 [-0.25, -0.12]	Trivial	< 0.001*
4		276.0 ± 38.8	268.0 ± 38.3	-8.00 ± 9.53	-0.20 [-0.27, -0.14]	Small	< 0.001*
5		276.9 ± 44.9	268.8 ± 43.1	-8.10 ± 8.60	-0.18 [-0.23, -0.13]	Trivial§	< 0.001*

Notes. [a] Smash factor calculated as $Ball_{peak\_R}/CHS_{peak}$, $Ball_{peak\_R}$, Resultant peak ball speed; CHS, Clubhead speed; ES, Effect size; LL, Lower confidence limit; MBI, Magnitude-based inference; UL, Upper confidence limit; §, Likelihood > 75%. Grey fill indicates a non-trivial, significant ($p < 0.05$), and likely (> 75% likely) effect; *, *p*-value < 0.05.

Table 12. Peak angular velocity parameters (mean ± standard deviation) with control and SuperSpeed warm-up protocols in high level amateur golfers (*n* = 12). Effect of SuperSpeed warm-up expressed using change in mean, effect size [95% confidence limits], magnitude-based inference, and paired *t*-test *p*-value statistics.

Set	**Parameters**	**Control**	**SuperSpeed**	**Change**	**ES [LL, UL]**	**MBI**	***p*-value**
1	Peak angular velocity of torso (°/s)	700.5 ± 73.5	718.6 ± 81.7	18.2 ± 21.3	0.24 [0.16, 0.32]	Small§	< 0.001*
2		704.6 ± 75.4	713.1 ± 83.0	8.6 ± 19.8	0.11 [0.04, 0.18]	Trivial§	0.003*
3		700.3 ± 77.7	714.2 ± 77.6	13.9 ± 16.1	0.18 [0.12, 0.23]	Trivial§	< 0.001*
4		699.4 ± 78.9	712.1 ± 83.6	12.7 ± 16.5	0.16 [0.10, 0.21]	Trivial§	< 0.001*
5		707.7 ± 73.0	720.6 ± 78.7	12.9 ± 16.0	0.17 [0.12, 0.23]	Trivial§	< 0.001*
1	Peak angular velocity of lead arm (°/s)	1053.8 ± 107.9	1089.8 ± 111.0	36.0 ± 43.7	0.33 [0.22, 0.44]	Small§	< 0.001*
2		1051.7 ± 114.8	1074.0 ± 115.7	22.2 ± 41.8	0.19 [0.09, 0.29]	Trivial§	< 0.001*
3		1051.1 ± 107.6	1075.9 ± 113.5	24.8 ± 33.7	0.23 [0.14, 0.31]	Small	< 0.001*
4		1049.8 ± 106.0	1071.0 ± 118.6	21.2 ± 36.5	0.20 [0.11, 0.29]	Trivial	< 0.001*
5		1062.3 ± 106.3	1083.5 ± 114.5	21.2 ± 34.1	0.20 [0.11, 0.28]	Trivial	< 0.001*
1	Peak angular velocity of club (°/s)	2142.9 ± 200.6	2208.9 ± 205.7	66.0 ± 79.4	0.32 [0.22, 0.43]	Small§	< 0.001*
2		2147.8 ± 204.0	2196.4 ± 201.7	48.6 ± 86.9	0.23 [0.12, 0.35]	Small	< 0.001*
3		2139.0 ± 198.5	2182.9 ± 186.5	43.9 ± 102.6	0.22 [0.08, 0.35]	Small	0.002*
4		2149.2 ± 190.3	2194.0 ± 192.7	44.8 ± 86.5	0.23 [0.11, 0.35]	Small	< 0.001*
5		2173.8 ± 215.1	2221.8 ± 193.3	48.0 ± 103.2	0.22 [0.09, 0.35]	Small	0.001*

Notes. ES, Effect size; LL, Lower confidence limit; UL, Upper confidence limit; MBI, Magnitude-based inference; §, Likelihood > 75%; Grey fill indicates a non-trivial, significant ($p < 0.05$), and likely (> 75% likely) effect; *, *p*-value < 0.05.

Table 13. Centre of mass (COM) parameters (mean ± standard deviation) with control and SuperSpeed warm-up protocols in high level amateur golfers ($n = 12$). Effect of SuperSpeed warm-up expressed using change in mean, effect size [95% confidence limits], magnitude-based inference, and paired *t*-test *p*-value statistics.

Set	Parameters	Standard	Control	Change	ES [LL, UL]	MBI	*p*-value
1	COM at top X (cm)	-5.76 ± 2.41	-5.17 ± 2.40	0.59 ± 0.92	0.24 [0.14, 0.34]	Small§	< 0.001*
2		-5.55 ± 2.32	-5.06 ± 2.13	0.49 ± 0.90	0.21 [0.10, 0.31]	Small	< 0.001*
3		-5.81 ± 2.43	-5.28 ± 2.62	0.53 ± 0.84	0.21 [0.12, 0.31]	Small	< 0.001*
4		-5.70 ± 2.50	-5.32 ± 2.56	0.38 ± 1.11	0.15 [0.03, 0.27]	Trivial§	0.015
5		-5.46 ± 2.50	-5.38 ± 2.70	0.08 ± 1.04	0.03 [-0.08, 0.15]	Trivial§	0.585
1	COM at impact-minimum Y (cm)	-2.14 ± 1.03	-2.48 ± 1.04	-0.34 ± 0.41	-0.32 [0.00, 0.00]	Small§	< 0.001*
2		-2.17 ± 1.48	-2.40 ± 1.41	-0.23 ± 0.77	-0.15 [-0.30, -0.00]	Trivial	0.043
3		-2.04 ± 1.09	-2.45 ± 1.14	-0.41 ± 0.70	-0.37 [-0.55, -0.20]	Small§	< 0.001*
4		-1.95 ± 1.40	-2.21 ± 1.34	-0.26 ± 0.73	-0.18 [-0.32, -0.04]	Trivial	0.013
5		-1.90 ± 1.86	-2.22 ± 1.59	-0.32 ± 1.10	-0.17 [-0.33, 0.00]	Trivial	0.047

Notes. COM, Centre of mass; X, Medial/lateral direction; Y, Anterior/posterior direction; ES, Effect size; LL, Lower confidence limit; UL, Upper confidence limit; MBI, Magnitude-based inference; §, Likelihood > 75%; Grey fill indicates a non-trivial, significant ($p < 0.05$), and likely (> 75% likely) effect; *, *p*-value < 0.05.

Discussion

Clubhead speed is the key parameter linked with financial earnings[3,39] and golf performance [24,47,48,173,174], which has led to players using various warm-up strategies pre-tournament to enhance clubhead speeds. SuperSpeed Golf™ claims that 600 professional golfers use their weighted club products[187], which the company states can enhance swing performance and clubhead speed up to 30 minutes post use. In the current study, incorporating the SuperSpeed weighted clubs in a warm-up led to meaningful acute improvements in clubhead speed compared to a control golf-specific warm-up condition (2.6 mph, **Table 11**) in the first set of five swings performed 90 seconds post warm-up. However, from the second set of five swings onwards, changes in clubhead speed between warm-up conditions became trivial. From a biomechanical perspective, potentiation of clubhead speed with the SuperSpeed warm-up was associated with quicker downswing times; increased peak torso, lead arm, and club angular velocities; and COM positions closer to the target direction at the top of backswing and more to the left of the target line (i.e., posterior direction) at impact. However, like clubhead speed, these biomechanical changes became either trivial, non-significant, or less than 75% likely from the second set onwards (**Table 12** and **Table 13**) compared to a control warm-up. Additionally, there was no significant or meaningful improvements in ball speeds when contrasting SuperSpeed to control warm-up conditions (**Table 11**), leading to a moderately impaired smash factor in Set 1 that tended to persist into Set 2. Overall, our findings indicate that the potentiation effect from the SuperSpeed weighted clubs and warm-up protocol does not persist past the initial swing bout (i.e., first set of five swings), with any on-course effect on driving performance lasting for the duration of the first hole only.

In contrast to previous research on PAP confirming a potentiation effect across several performance bouts and persistence of effects up to 18.5 minutes[125,139,150,210], the SuperSpeed warm-up condition did not produce any significant or meaningful effect from the second set of five swings onwards during a golf-simulated task compared to a control warm-up. After the first set, the combined time of rest (90 s) and 400 m walk (6 minutes) was 7.5 minutes. The structure of our experimental protocol meant that three sets could be completed in approximately 30 minutes, the timeframe SuperSpeed Golf^{TM} claims swing performance remains enhanced following their warm-up protocol[178]. On-course, players would complete three tee shots within this 30-minute window[218]. However, differences between SuperSpeed and control warm-up conditions noted in the first set became either non-significant or trivial from the second set, which began 14 minutes post warm-up. Previous research investigating the persistence of potentiation with high-level athletes has indicated improvements in subsequent performance from 4 to 12 minutes[127,141,154]. Participants within this study were of a high level amateur standard (handicap < 3.0), potentially explaining the lack of persistence of the effect. Individualised responses were not examined herein, which could also mask persistence of effects.

As introduced earlier, the intensity of the PAP-inducing exercise can influence the persistence of effect. PAP-inducing exercises typically comprise of an exercise performed at greater than 90% of 1RM in other sports[123,125,127,135,141,154,210]. Lowrey et al.[141] found that using PAP-inducing exercises with a moderate (70% 1RM) or heavy (93% 1RM) load increased vertical jump height 4 and 8 minutes post exercise, with only the heavy load condition associated with improved performance at 12 minutes. The persistence of the PAP effect has also been shown to differ between unloaded (body mass) and loaded (body mass +10%) plyometric single leg bounds[139]. After loaded single leg bounds, sprinting performance was significantly improved at both 4 and 8 minutes, but only at 4 minutes for the unloaded bounds. Overall, research indicates that increased-intensity PAP-inducing exercises may prolong the duration of the positive effects due to the greater increase in muscle recruitment and neural activation[139,141]. The relatively low loads of the SuperSpeed weighted clubs could explain the lack of persistence of potentiation. However, previous research in baseball has illustrated that the use of equipment greater than 10% of standard bat mass resulted in altered biomechanics to that required during the sporting task[145,148]. Therefore, the use of weighted clubs heavier than the SuperSpeed clubs used during a warm-up may produce a detrimental effect on an athlete's biomechanics and therefore performance.

This research was designed to investigate the effect of using weighted clubs marketed to improve performance[178] on actual swing performance. The control warm-up was designed to replicate a habitual warm-up routine prior to tournament play, and consisted of 26 swings that progressed in intensity, load, and speed. The control warm-up protocol was hence similar to the SuperSpeed warm-up, which contained 28 swings that progressed in intensity at various loads (**Figure 7**). Without the comparison to a “no-warm-up” or “non golf-specific warm-up”, the potentiation developed from the SuperSpeed warm-up protocol can only be compared to the potentiation developed from the control warm-up. Green[219] found that competitive golfers alter swing biomechanics and improve driving distance by 10 metres compared to baseline after walking 500 m speculatively due to improved segmental coordination, resulting in better ball striking and greater distances through the summation of forces[33,79,93,220]. On this basis, clubhead and ball speeds of our golfers in Set 2 might have exceeded those from Set 1 in both warm-up conditions, which was not readily apparent (**Table 11**). The lack of carry-over and limited persistence of potentiation from the SuperSpeed warm-up protocol from Set 1 to Set 2 is likely due to a reduction in potentiation rather than an accumulation of fatigue. Multiple studies have investigated the accumulation of fatigue during an 18-hole and 36-hole round of golf, reporting a significant increase in mental and physical fatigue, and a decrease in iron accuracy and driving distance towards the end of the round[21,209,217,221]. Our protocol measured the persistence of any potentiation effect equivalent to completing five holes based on walking distance and time[214-218]. Fatigue is minimal at such an early stage of the round (holes 1 to 6), with no significant difference in salivary endocrine markers compared to baseline seen in elite male golfers[221]. As such, we suggest that fatigue was not an overt confounder in our study findings, and would not influence performance.

To mitigate reductions in potentiation, previous research has incorporated the use of re-warm-up PAP strategies prior to second-half sporting performances[104,222-224]. Zois et al.[224] implemented a 5RM leg press as a re-warm-up strategy that resulted in improved repeated sprints, countermovement jumps, and sport-specific performance subsequently. The 2.6 mph acute increase in clubhead speed following the SuperSpeed warm-up could lead to considerable enhancements in golfer’s performance[24,47,48,173,174]. However, the R&A rules of golf prohibit the use of training aids (such as SuperSpeed clubs) that can potentially advantage a player during a round[225], precluding the use of the SuperSpeed clubs as a re-warm-up strategy in tournament play. Future research could investigate the effects of using a players own clubs as a re-warm-up strategy following the SuperSpeed protocol in an attempt to re-induce potentiation in the field.

The SuperSpeed warm-up protocol sequence uses clubs of different weights in a particular order (heavy to light to mid-weight to heavy, **Figure 7**) unlike any previous PAP-inducing research in ball striking sports[85,143-148], making direct comparisons to these other studies challenging. Reyes and Dolny[85] researched how various sequencing and pairing of using a light, standard, and heavy baseball bat during a warm-up influenced subsequent batting speed. Compared to the control warm-up using a standard bat, all weighted bat warm-up protocols improved bat speed; however, none of the improvements were statistically significant. The standard to light to heavy warm-up sequence improved bat speed the most (6.03%), followed by using only a heavy bat (5.08%) and then the light to standard to heavy sequence (3.12%)[85]. The last sequence more closely reflects the SuperSpeed protocol associated with an 2.6 mph (2.59%) increase in clubhead speed in Set 1. As such, a different sequencing of the SuperSpeed weighted clubs might have been of greater benefit. The SuperSpeed warm-up incorporates both overspeed (lighter clubs) and heavy-resistance (heavier clubs) PAP-inducing exercises, finishing with one swing of the lightest club. The three protocols examined by Reyes and Dolny[85] that finished with the light baseball bat resulted in non-significant increases in bat speeds less than 2.84%[85]. Therefore, the mechanism that contributes the most to the acute enhancement in clubhead speed, light or heavy club, is unclear and requires research that is more mechanistic in nature. Currently the optimal dosage, load, and sequence for SuperSpeed Golf™ is unknown, with a limitation in our research being not capturing the 3D biomechanics of participants during the weighted club warm-up to monitor potential alterations in movement patterns. Future studies could investigate whether changing the order of the weighted clubs within the SuperSpeed warm-up protocol or using lighter or heavier clubs affects clubhead potentiation and movement specificity to confirm whether the current sequence and protocol is optimal.

Although the acute enhancement in performance did not persist beyond the first set, it is noteworthy that there were no detrimental effects from using the weighted clubs as part of warm-up on clubhead speed or biomechanical performance measures, except for the smash factor. The significant negative *moderate* effect of the SuperSpeed warm-up on the smash factor (i.e., transfer of clubhead to ball speed) is likely due to only 25% of participants reporting previous experience using the clubs. The changes in biomechanical patterning – albeit few and small – and acute increase in clubhead speed subsequent the SuperSpeed warm-up was most likely unfamiliar to participants. The centeredness of strike[174,200,201] can affect ball launch conditions[174,203] and driving distance, accuracy, and scoring[4,15,18]. Data from the three participants with previous SuperSpeed experience indicate an increase in clubhead speed (1.84 ± 3.64 m/s, $p < 0.001$) and ball speed (1.17 ± 2.07 m/s, $p = 0.034$) with no effect of the protocol on smash factor (change: 0.006 ± 0.053, $p = 0.656$). This exploratory analysis provides preliminary support that prior exposure to the SuperSpeed warm-up protocol may enhance transference of increased clubhead to ball speeds and consolidate mastery of supramaximal movement patterns, although confirmatory studies are needed with larger sample sizes and targeted study designs. If the control condition smash factor of 1.42 was maintained after the SuperSpeed warm up, ball speed would have increased by 3.25 mph, equating to an increased carry distance of 5.5 metres[40]. Therefore, integration of the SuperSpeed clubs into training and competition on a regular basis to increase exposure and experience to the protocol might lead to a greater transference of the observed increase in clubhead speed to the ball, and ultimately driving distance and performance[150].

One limitation of this study was the set time of 7.5 minutes between the end of the first set and start of the second set of recorded trials, which does not allow for a detailed minute-to-minute time course analysis to the SuperSpeed potentiation. That said; our study design meant to replicate the on-field nature of driving performances of a golf tournament, making the study more ecologically valid. Since a PAP-inducing warm-up can potentiate performance from 2 to 18.5 minutes[140,150] post-stimulus, we expected persistence of effects to last at least to Set 2 of our golf-simulated experiment. An additional limitation was that participant strength levels were not tested or monitored. Previous research has illustrated an association between strength levels and potentiation effects of PAP induced using squat[127,135,150,154,210,226], power clean[135], hex bar deadlift[140], and bench press[127] exercises. Although all our golfers had at least 1 year of resistance training experience, it could be that golfers with increased strength levels would benefit more from use of weighted clubs as part of warm-up. Another limitation of this study is the laboratory-based environment, which is a frequent limitation in biomechanical studies of golf[35,42,44]. As summarised elsewhere[76], the artificial environment of laboratories and surrogate performance measures used might not accurately reflect on-course performance. The use of a net, for instance, limits the ability of golfers to focus on a driving target, and covering the golf ball in reflective tape would have altered its aerodynamic properties[227]. Generalisation of our laboratory-based findings regarding the acute and persistence of PAP effects from the SuperSpeed warm-up protocol warrants further research.

Conclusion

The use of the SuperSpeed Golf™ weighted clubs warm-up protocol compared to a golf-specific control warm-up protocol produced no significant or meaningful difference in clubhead speed; smash factor; peak angular velocities of the torso and lead arm; or COM measures following an initial first set of five swings. The acute improvements in clubhead speed (2.6 mph) seen in our golfers in the first set of five swings may significantly influence on-course performance[24,47,48,173,174]; however, there was a lack of transference of enhanced clubhead speed to the ball likely due to lack of prior exposure of our participants to the SuperSpeed warm-up protocol and supramaximal movement patterns. Overall, our findings imply that after use of the SuperSpeed Golf™ warm-up protocol, golfers can expect an increase in driving performance on the first tee shot, with trivial effects from the second tee onwards. The financial, time, and practical value of investing in the SuperSpeed Golf™ product is therefore questioned especially given that use of ergogenic aids during tournament play is prohibited[225].

Chapter Five: Discussion and Conclusion

Summary

Systematic reviews of articles relating to (1) golf and 3D biomechanics, and (2) weighted equipment used during a warm-up in ball striking sports were completed as part of this Thesis, with the methodological quality of each article assessed using the Effective Public Health Practice Project (EPHPP) tool. Of the 23 studies quality assessed on golf and 3D biomechanics, only two studies achieved a strong quality score. The biomechanical measures most consistently reported to relate to clubhead and ball speed across these 23 articles were pelvis and torso axial rotation, rotational speed, X-factor, and X-factor stretch. All seven studies on weighted equipment used during a warm-up for ball striking sports were on baseball, and only one study achieved a strong quality score. None of these studies found a meaningful benefit of a weighted equipment warm-up on subsequent swing performance. Altogether, these findings highlighted the need for better quality methodological studies in the area, especially regarding the use of weighted equipment in golf as means to enhance subsequent performance

Two experimental studies were then undertaken to examine the (1) acute and (2) persistence of the potentiation effects of using weighted clubs (SuperSpeed Golf™) as part of warm-up on golf driving performance in competitive golfers. The SuperSpeed warm-up protocol led to significant ($p < 0.05$) *small* (ES > 0.2) and likely (greater than 75% likelihood) changes in clubhead speed (2.6 mph); angular velocity of the torso, lead arm, and club; and two centre of mass (COM) variables compared to a golf-specific control warm-up in an initial set of five swings. However, no significant changes were seen in ball speed, resulting in a *moderate* and significant decline in the smash factor. After the golfers walked the distance of a simulated hole, the initial changes observed in golf swing biomechanics were no longer meaningful.

Practical applications

From this Thesis, several practical implications can be advanced. The reviewed literature on golf and 3D biomechanics illustrates that highly-skilled golfers (handicap < 5.0) should focus on pelvis and torso axial rotation, pelvis and torso rotational velocity, X-factor, and X-factor stretch measures as significantly related to clubhead and ball speed. From the literature reviewed on weighted equipment used during a warm-up for ball striking sports, it was found that the weighted equipment warm-up was either ineffective or detrimental to performance in terms of batting speed in baseball. Overall, the second literature review highlighted the limited understanding and practical justification regarding the use of weighted equipment as part of warm-ups in ball striking sport, especially in golf. Our first study found that the use of the SuperSpeed warm-up protocol significantly enhanced clubhead speed (2.6 mph), a measure previously associated with skill level, handicap, and scoring[24,47,48,173,174]. However, no significant change was seen in ball speed, with a resultant negative effect on smash factor (strike efficiency). The persistence of the enhanced performance measures (i.e., clubhead speed and angular velocities of the torso, lead arm, and club) following the SuperSpeed protocol, however, did not persist the duration of one simulated golf hole (i.e., 400 m treadmill walk). Overall, our findings indicate that the SuperSpeed warm-up potentiates clubhead speed and peak angular velocity of segments acutely compared to a similar golf-specific warm-up using standard golf clubs. However, this potentiation did not lead to an increase in ball speed, impaired the smash factor acutely, and did not persist to the second set of swings. Hence, the value of investing in SuperSpeed weighted clubs is questionable. The finding from our study do not support the claims of SuperSpeed Golf™ that using their weighted clubs and warm-up protocol potentiates performance for up to 30 minutes.

Strengths

The findings of this Thesis add to the existing literature on the effects of warm-up strategies on sports performance. The systematic reviews and quality appraisal of golf and 3D biomechanics literature and weighted equipment used during a warm-up in ball striking sports highlight the need for better quality studies in the area, with targeted studies on weighted equipment warm-ups in golf to justify the current on-course practices and SuperSpeed Golf™ claims. Therefore, this Thesis investigated the use of weighted equipment (SuperSpeed Golf™) during a warm-up and measured subsequent acute and persistence of potentiation effects on golf driving performance and biomechanics. The SuperSpeed warm-up protocol was assessed against a golf-specific warm-up protocol designed to replicate a typical warm-up prior to a competition. The results are therefore of considerable relevance to the golfing community as this research compares a novel warm-up protocol (SuperSpeed Golf^{TM}) to current practice. Six hundred professional golfers on tour supposedly use the SuperSpeed warm-up protocol[187]; but until now, no empirical evidence was available to support these practices. To enhance the relevance of this Thesis, golfers of a relatively high standard participated in the two experimental studies (high level amateur golfers, handicap 0.6 ± 1.8). Additionally, sample size calculations[189] deemed the number of participants sufficient to identify previously reported minimal detectable changes in clubhead speed at the 5% significance level with 80% power[28,190]. Although previous research illustrates excellent between session reliability of 3D biomechanics measures in sport[207], the same examiner positioned all markers on participants and the two experimental conditions were randomised to mitigate the effect of different 3D marker position between sessions on outcomes.

Limitations

A few limitations to this Thesis are acknowledged. The set duration of a golf-simulated hole (7.5 minutes) between testing trials does not allow for a detailed minute-to-minute time course analysis of the potentiation effect. That said; our study was designed to replicate the on-field nature of driving performances during a golf tournament, making the study more ecologically valid. Additionally, not having a "no-warm up" condition or "non golf-specific warm up" protocol was a limitation as both warm-ups used in this research could have resulted in a level of performance altering potentiation. Another limitation of this study is the laboratory-based environment of experimentation. As summarised elsewhere[76], the artificial environment of laboratories and surrogate performance measures used might not accurately reflect on-field performance. No testing was done to monitor the influence of placing reflective tape around the golf ball on the aerodynamic properties of the ball and related biomechanical variables. Additionally, the use of a net, limits the ability of golfers to focus on a driving target. Therefore, driving accuracy measures were not analysed in this research. Although participant sample size and the reliability of 3D biomechanical measures were sufficiently high based on prior research[28,190], no test-retest reliability study of the specific protocol and set-up used in this Thesis was undertaken. Lastly, previous research has shown significant levels of individualised response variance to a PAP stimulus[125], which was not overtly considered and analysed in this Thesis.

Future research

From this Thesis, a number of avenues for future research can be recommended. The lack of research in ball striking sports outside of baseball and the generally weak quality of articles in both golf and 3D biomechanics, and weighted equipment warm-ups in ball striking sports highlight the need for better quality studies. The experimental studies in this Thesis used the prescribed SuperSpeed Golf^{TM} weighted clubs and warm-up protocol. Future research should investigate variations on the sequencing and weight of the clubs used during the warm-up to confirm whether the current sequence and protocol is optimal in terms of potentiating clubhead speed and golf performance at varying skill levels. Furthermore, investigating whether using a player's own clubs as a re-warm-up strategy following the SuperSpeed protocol can re-induce potentiation might provide a practical solution that respects the rules of golf. Additionally, future research could implement a more specific minute-to-minute study design and data analysis to allow for a better understanding of the persistence of the effects associated with the SuperSpeed warm-up protocol.

Bibliography

1. Australia G. *Golf club participation report.* Austraila: Golf Austraila; 8th May 2019. 2018.
2. Golf NZ. *New Zealand golf annual report & statement of accounts.* New Zealand: New Zealand Golf; 8th May 2019. 2018.
3. Tour P. PGA tour statistics (money earnings). PGA Tour. https://www.pgatour.com/players/player.36689.brooks-koepka.html. Published 2019. Accessed 21st May, 2019.
4. Hellstrom J. Competitive elite golf: A review of the relationships between playing results, technique and physique. *Sports Medicine (Auckland, NZ).* 2009;39(9):723-741.
5. Fried HO, Lambrinos J, Tyner J. Evaluating the performance of professional golfers on the PGA, LPGA and SPGA tours. *European Journal of Operational Research.* 2004;154(2):548-561.
6. Dorsel TN, Rotunda RJ. Low scores, top 10 finishes, and big money: An analysis of professional golf association tour statistics and how these relate to overall performance. *Perceptual and Motor Skills.* 2001;92(2):575-585.
7. Engelhardt GM. Differences in shot-making skills among high and low money winners on the PGA tour. *Perceptual and Motor Skills.* 1997;84(3 Pt 2):1314.
8. Finley PS, Halsey JJ. Determinants of PGA tour success: An examination of relationships among performance, scoring, and earnings. *Perceptual and Motor Skills.* 2004;98(3 Pt 1):1100-1106.
9. Quinn RJ. Exploring correlation coefficients with golf statistics. *Teaching Statistics.* 2006;28(1):10-13.
10. Allen T, Bowley A, Wood P, Henrikson E, Morales E, James D. Effect of temperature on golf ball dynamics. *Procedia Engineering.* 2012;34:634-639.
11. Carlsson M, Nilsson J, Hellström J, Tinmark F, Carlsson T. The effect of ball temperature on ball speed and carry distance in golf drives. *Proceedings*

of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology. 2018.

12. James N, Rees GD. Approach shot accuracy as a performance indicator for US PGA tour golf professionals. *International Journal of Sports Science & Coaching.* 2008;3:145-160.
13. Sen KC. Mapping statistics to success on the PGA tour. *Sport, Business and Management: An International Journal.* 2012;2(1):39-50.
14. Broadie M. Assessing golfer performance on the PGA tour. *Interfaces.* 2012;42(2):146-165.
15. Hellstrom J, Nilsson J, Isberg L. Drive for dough. PGA tour golfers tee shot functional accuracy, distance and hole score. *Journal of Sports Sciences.* 2014;32(5):462-469.
16. Hume PA, Keogh J, Reid D. The role of biomechanics in maximising distance and accuracy of golf shots. *Sports Medicine (Auckland, NZ).* 2005;35(5):429-449.
17. Brown SJ, Nevill AM, Monk SA, Otto SR, Selbie WS, Wallace ES. Determination of the swing technique characteristics and performance outcome relationship in golf driving for low handicap female golfers. *Journal of Sports Sciences.* 2011;29(14):1483-1491.
18. Stockl M, Lamb PF. The variable and chaotic nature of professional golf performance. *Journal of Sports Sciences.* 2018;36(9):978-984.
19. Fletcher IM, Hartwell M. Effect of an 8-week combined weights and plyometrics training program on golf drive performance. *The Journal of Strength and Conditioning Research.* 2004;18(1):59-62.
20. Robertson S, Burnett AF, Gupta R. Two tests of approach-iron golf skill and their ability to predict tournament performance. *Journal of Sports Sciences.* 2014;32(14):1341-1349.
21. Mumford PW, Tribby AC, Poole CN, et al. Effect of caffeine on golf performance and fatigue during a competitive tournament. *Medicine and Science in Sports and Exercise.* 2015.
22. Nesbit SM. Development of a full-body biomechanical model of the golf swing. *International Journal of Modelling and Simulation.* 2015;27(4):392-404.

23. Farrally MR, Cochran AJ, Crews DJ, et al. Golf science research at the beginning of the twenty-first century. *Journal of Sports Sciences.* 2003;21(9):753-765.
24. Sell TC, Tsai YS, Smoliga JM, Myers JB, Lephart SM. Strength, flexibility, and balance characteristics of highly proficient golfers. *The Journal of Strength and Conditioning Research.* 2007;21(4):1166-1171.
25. Balzerson D, Banerjee J, McPhee J. A three-dimensional forward dynamic model of the golf swing optimized for ball carry distance. *Sports Engineering.* 2016;19(4):237-250.
26. Lange G, Dillman C. How has biomechanics contributed to the understanding of the golf swing? *Science and Golf II.* 2002:24-33.
27. van der Kruk E, Reijne M. Accuracy of human motion capture systems for sport applications; state of the art review. *European Journal of Sport Science.* 2018;18(6):806-819.
28. Outram T, Wheat J. Test-retest reliability of segment kinetic energy measures in the golf swing. *Sports Biomechanics.* 2019:1-16.
29. Joyce C. The most important "factor" in producing clubhead speed in golf. *Human Movement Science.* 2017;55:138-144.
30. Sorbie GG, Gu Y, Baker JS, Ugbolue UC. Analysis of the X-factor and X-factor stretch during the completion of a golf practice session in low-handicap golfers. *International Journal of Sports Science & Coaching.* 2018;13(6):1001-1007.
31. Cole MH, Grimshaw PN. The biomechanics of the modern golf swing: Implications for lower back injuries. *Sports Medicine (Auckland, NZ).* 2016;46(3):339-351.
32. Langdown BL, Bridge M, Li FX. Movement variability in the golf swing. *Sports Biomechanics.* 2012;11(2):273-287.
33. Neal R, Lumsden R, Holland M, Mason B. Body segment sequencing and timing in golf. *International Journal Of Sports Science & Coaching.* 2016;2:25-36.
34. Healy A, Moran KA, Dickson J, et al. Analysis of the 5 iron golf swing when hitting for maximum distance. *Journal of Sports Sciences.* 2011;29(10):1079-1088.

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

36. Horan SA, Kavanagh JJ. The control of upper body segment speed and velocity during the golf swing. *Sports Biomechanics.* 2012;11(2):165-174.

37. Joyce C, Burnett A, Cochrane J, Ball K. Three-dimensional trunk kinematics in golf: Between-club differences and relationships to clubhead speed. *Sports Biomechanics.* 2013;12(2):108-120.

38. Kwon YH, Han KH, Como C, Lee S, Singhal K. Validity of the X-factor computation methods and relationship between the X-factor parameters and clubhead velocity in skilled golfers. *Sports Biomechanics.* 2013;12(3):231-246.

39. Tour P. PGA tour statistics (season average clubhead velocity). PGA Tour. https://www.pgatour.com/stats/stat.02401.2018.html. Published 2018. Accessed 30th September, 2018.

40. Trackman. 2017 PGA and LPGA tour average. https://blog.trackmangolf.com/2017-pga-lpga-tour-avg/. Published 2017. Accessed 3rd June, 2019.

41. Zheng N, Barrentine SW, Fleisig GS, Andrews JR. Kinematic analysis of swing in pro and amateur golfers. *International Journal of Sports Medicine.* 2008;29(6):487-493.

42. Steele KM, Roh EY, Mahtani G, Meister DW, Ladd AL, Rose J. Golf swing rotational velocity: The essential follow-through. *Annals of Biomedical Engineering.* 2018;42(5):713-721.

43. McNally MP, Yontz N, Chaudhari AM. Lower extremity work is associated with club head velocity during the golf swing in experienced golfers. *International Journal of Sports Medicine.* 2014;35(9):785-788.

44. Meister DW, Ladd AL, Butler EE, et al. Rotational biomechanics of the elite golf swing: Benchmarks for amateurs. *Journal of Applied Biomechanics.* 2011;27(3):242-251.

45. Fedorcik GG, Queen RM, Abbey AN, Moorman CT, 3rd, Ruch DS. Differences in wrist mechanics during the golf swing based on golf handicap. *Journal of Science and Medicine in Sport.* 2012;15(3):250-254.

46. Ferdinands RED, Kersting UG, Marshall RN. A twenty-segment kinematics and kinetics model for analysing golf swing mechanics. *Sports Technology.* 2014;6(4):184-201.
47. Lewis AL, Ward N, Bishop C, Maloney S, Turner AN. Determinants of club head speed in PGA professional golfers. *The Journal of Strength and Conditioning Research.* 2016;30(8):2266-2270.
48. Fradkin AJ, Sherman CA, Finch CF. How well does club head speed correlate with golf handicaps? *Journal of Science and Medicine in Sport.* 2004;7(4):465-472.
49. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Annals of Internal Medicine.* 2009;151(4):264-269.
50. Project EPHP. Quality assessment tool for quantitative studies. In: Effective Public Health Practice Project Hamilton, ON; 1998.
51. Armijo-Olivo S, Stiles CR, Hagen NA, Biondo PD, Cummings GG. Assessment of study quality for systematic reviews: A comparison of the cochrane collaboration risk of bias tool and the Effective Public Health Practice Project quality assessment tool: Methodological research. *Journal of Evaluation in Clinical Practice.* 2012;18(1):12-18.
52. Varley-Campbell J, Cooper C, Wilkerson D, Wardle S, Greeves J, Lorenc T. Sex-specific changes in physical performance following military training: A systematic review. *Sports Medicine (Auckland, NZ).* 2018;48(11):2623-2640.
53. Joyce C. An examination of the correlation amongst trunk flexibility, X-factor and clubhead speed in skilled golfers. *Journal of Sports Sciences.* 2017;35(20):2035-2041.
54. Beak SH, Choi A, Choi SW, et al. Upper torso and pelvis linear velocity during the downswing of elite golfers. *Biomedical Engineering Online.* 2013;12(1):13.
55. Choi A, Lee IK, Choi MT, Mun JH. Inter-joint coordination between hips and trunk during downswings: Effects on the clubhead speed. *Journal of Sports Sciences.* 2016;34(20):1991-1997.

56. Joyce C, Chivers P, Sato K, Burnett A. Multi-segment trunk models used to investigate the crunch factor in golf and their relationship with selected swing and launch parameters. *Journal of Sports Sciences.* 2016;34(20):1970-1975.

57. Zheng N, Barrentine SW, Fleisig GS, Andrews JR. Swing kinematics for male and female pro golfers. *International Journal of Sports Medicine.* 2008;29(12):965-970.

58. Joyce C, Burnett A, Cochrane J, Reyes A. A preliminary investigation of trunk and wrist kinematics when using drivers with different shaft properties. *Sports Biomechanics.* 2016;15(1):61-75.

59. Egret CI, Vincent O, Weber J, Dujardin FH, Chollet D. Analysis of 3D kinematics concerning three different clubs in golf swing. *International Journal of Sports Medicine.* 2003;24(6):465-470.

60. Horan SA, Evans K, Kavanagh JJ. Movement variability in the golf swing of male and female skilled golfers. *Medicine and Science in Sports and Exercise.* 2011;43(8):1474-1483.

61. Horan SA, Evans K, Morris NR, Kavanagh JJ. Thorax and pelvis kinematics during the downswing of male and female skilled golfers. *Journal of Biomechanics.* 2010;43(8):1456-1462.

62. Joyce C, Burnett A, Ball K. Methodological considerations for the 3D measurement of the X-factor and lower trunk movement in golf. *Sports Biomechanics.* 2010;9(3):206-221.

63. Betzler NF. *The effect of differing shaft dynamics on the biomechanics of the golf swing*, Edinburgh Napier University; 2010.

64. Sweeney M, Mills P, Mankad A, Elliott B, Alderson J. Wrist kinematics during the golf drive from a bilaterally anatomical perspective. Paper presented at: ISBS-Conference Proceedings Archive2012.

65. Kwon YH, Como CS, Singhal K, Lee S, Han KH. Assessment of planarity of the golf swing based on the functional swing plane of the clubhead and motion planes of the body points. *Sports Biomechanics.* 2012;11(2):127-148.

66. Aguinaldo AL, Buttermore J, Chambers H. Effects of upper trunk rotation on shoulder joint torque among baseball pitchers of various levels. *Journal of Applied Biomechanics.* 2007;23(1):42-51.

67. Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. *Journal of Orthopaedic Research.* 1990;8(3):383-392.

68. Fradkin AJ, Sherman CA, Finch CF. Improving golf performance with a warm up conditioning programme. *British Journal of Sports Medicine.* 2004;38(6):762-765.

69. Cardinale M, Newton R, Nosaka K, Cardinale M, Newton R, Nosaka K. *Strength and conditioning : biological principles and practical applications.* New York: New York: John Wiley & Sons, Incorporated; 2010.

70. Brown SJ, Selbie WS, Wallace ES. The X-Factor: An evaluation of common methods used to analyse major inter-segment kinematics during the golf swing. *Journal of Sports Sciences.* 2013;31(11):1156-1163.

71. Meister DW, Schroeder JL, Butler EE, Twist KF, Ladd AL, Rose J. Kinematic and kinetic analysis of the elite golf swing. Paper presented at: Isbs-Conference Proceedings Archive 2007.

72. Cheetham PJ, Martin PE, Mottram R, St Laurent B. The importance of stretching the "X-factor" in the downswing of golf: The "X-factor stretch". *Optimising Perforamance in Golf.* 2001:192-199.

73. Burden AM, Grimshaw PN, Wallace ES. Hip and shoulder rotations during the golf swing of sub-10 handicap players. *Journal of Sports Sciences.* 1998;16(2):165-176.

74. Okuda I, Gribble P, Armstrong C. Trunk rotation and weight transfer patterns between skilled and low skilled golfers. *Journal of Sports Science and Medicine.* 2010;9(1):127-133.

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

76. Evans K, Tuttle N. Improving performance in golf: Current research and implications from a clinical perspective. *Brazilian Journal of Physical Therapy.* 2015;19(5):381-389.
77. Moore LJ, Vine SJ, Wilson MR, Freeman P. The effect of challenge and threat states on performance: An examination of potential mechanisms. *Psychophysiology.* 2012;49(10):1417-1425.
78. Egret CI, Nicolle B, Dujardin FH, Weber J, Chollet D. Kinematic analysis of the golf swing in men and women experienced golfers. *International Journal of Sports Medicine.* 2006;27(6):463-467.
79. Keogh JWL, Hume PA. Evidence for biomechanics and motor learning research improving golf performance. In. Vol 11: Taylor & Francis Group; 2012:288-309.
80. Fleisig GS, Kwon Y-H. Editorial. *Sports Biomechanics.* 2011;10(4):269-269.
81. Zealand SN. *Striking with an Implement.* New Zealand: Sport New Zealand;2017.
82. Laughlin WA, Fleisig GS, Aune KT, Diffendaffer AZ. The effects of baseball bat mass properties on swing mechanics, ground reaction forces, and swing timing. *Sports Biomechanics.* 2016;15(1):36-47.
83. Gray R. A model of motor inhibition for a complex skill: Baseball batting. *Journal of Experimental Psychology: Applied.* 2009;15(2):91-105.
84. Szymanski DJ, DeRenne C, Spaniol FJ. Contributing factors for increased bat swing velocity. *The Journal of Strength and Conditioning Research.* 2009;23(4):1338-1352.
85. Reyes GF, Dolny D. Acute effects of various weighted bat warm-up protocols on bat velocity. *The Journal of Strength and Conditioning Research.* 2009;23(7):2114-2118.
86. Dowling B, Fleisig GS. Kinematic comparison of baseball batting off of a tee among various competition levels. *Sports Biomechanics.* 2016;15(3):255-269.
87. Ibrahim R, Faber GS, Kingma I, van Dieen JH. Kinematic analysis of the drag flick in field hockey. *Sports Biomechanics.* 2017;16(1):45-57.

88. Lopez de Subijana C, Juarez D, Mallo J, Navarro E. Biomechanical analysis of the penalty-corner drag-flick of elite male and female hockey players. *Sports Biomechanics.* 2010;9(2):72-78.

89. Gergley JC. Acute effects of passive static stretching during warm-up on driver clubhead speed, distance, accuracy, and consistent ball contact in young male competitive golfers. *The Journal of Strength and Conditioning Research.* 2009;23(3):863-867.

90. Hume PA, Keogh J. Movement analysis of the golf swing. In: *Handbook Of Human Motion.* Cham: Springer International Publishing; 2018:1755-1772.

91. Gelen E, Dede M, Bingul BM, Bulgan C, Aydin M. Acute effects of static stretching, dynamic exercises, and high volume upper extremity plyometric activity on tennis serve performance. *Journal of Sports Science & Medicine.* 2012;11(4):600-605.

92. Tilley NR, Macfarlane A. Effects of different warm-up programs on golf performance in elite male golfers. *International Journal of Sports Physical Therapy.* 2012;7(4):388-395.

93. Gergley JC. Latent effect of passive static stretching on driver clubhead speed, distance, accuracy, and consistent ball contact in young male competitive golfers. *The Journal of Strength and Conditioning Research.* 2010;24(12):3326-3333.

94. Fradkin AJ, Zazryn TR, Smoliga JM. Effects of warming-up on physical performance: A systematic review with meta-analysis. *The Journal of Strength and Conditioning Research.* 2010;24(1):140-148.

95. Safran MR, Seaber AV, Garrett WE, Jr. Warm-up and muscular injury prevention. An update. *Sports Medicine (Auckland, NZ).* 1989;8(4):239-249.

96. Silva LM, Neiva HP, Marques MC, Izquierdo M, Marinho DA. Effects of warm-up, post-warm-up, and re-warm-up strategies on explosive efforts in team sports: A systematic review. *Sports Medicine (Auckland, NZ).* 2018;48(10):2285-2299.

97. McGowan CJ, Pyne DB, Thompson KG, Rattray B. Warm-up strategies for sport and exercise: Mechanisms and applications. *Sports Medicine (Auckland, NZ).* 2015;45(11):1523-1546.

98. Faulkner SH, Ferguson RA, Hodder SG, Havenith G. External muscle heating during warm-up does not provide added performance benefit above external heating in the recovery period alone. *European Journal of Applied Physiology.* 2013;113(11):2713-2721.

99. Faulkner SH, Ferguson RA, Gerrett N, Hupperets M, Hodder SG, Havenith G. Reducing muscle temperature drop after warm-up improves sprint cycling performance. *Medicine and Science in Sports and Exercise.* 2013;45(2):359-365.

100. Racinais S, Oksa J. Temperature and neuromuscular function. *Scandinavian Journal of Medicine and Science in Sports.* 2010;20:1-18.

101. Bailey SJ, Vanhatalo A, Wilkerson DP, Dimenna FJ, Jones AM. Optimizing the "priming" effect: Influence of prior exercise intensity and recovery duration on O2 uptake kinetics and severe-intensity exercise tolerance. *Journal of Applied Physiology.* 2009;107(6):1743-1756.

102. Bishop D. Warm up II: Performance changes following active warm up and how to structure the warm up. *Sports Medicine.* 2003;33(7):483-498.

103. Barnes MJ, Petterson A, Cochrane DJ. Effects of different warm-up modalities on power output during the high pull. *Journal of Sports Sciences.* 2017;35(10):976-981.

104. Mohr M, Krustrup P, Nybo L, Nielsen JJ, Bangsbo J. Muscle temperature and sprint performance during soccer matches beneficial effect of re-warm-up at half-time. *Scandinavian Journal of Medicine and Science in Sports.* 2004;14(3):156-162.

105. Behm DG, Blazevich AJ, Kay AD, McHugh M. Acute effects of muscle stretching on physical performance, range of motion, and injury incidence in healthy active individuals: A systematic review. *Applied Physiology, Nutrition, and Metabolism.* 2016;41(1):1-11.

106. Altavilla G, Gaetano R. Physiological effects of warm-up and problems related to team sports. *Sport Science.* 2018;11:83-88.

107. Gray SR, Soderlund K, Ferguson RA. ATP and phosphocreatine utilization in single human muscle fibres during the development of maximal power output at elevated muscle temperatures. *Journal of Sports Sciences.* 2008;26(7):701-707.

108. Gray SR, De Vito G, Nimmo MA, Farina D, Ferguson RA. Skeletal muscle ATP turnover and muscle fiber conduction velocity are elevated at higher muscle temperatures during maximal power output development in humans. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology.* 2006.
109. Gray SR, Soderlund K, Watson M, Ferguson RA. Skeletal muscle ATP turnover and single fibre ATP and PCr content during intense exercise at different muscle temperatures in humans. *Pflügers Archiv-European Journal of Physiology.* 2011;462(6):885-893.
110. Farina D, Arendt-Nielsen L, Graven-Nielsen T. Effect of temperature on spike-triggered average torque and electrophysiological properties of low-threshold motor units. *Journal of Applied Physiology.* 2005;99(1):197-203.
111. De Ruiter CJ, De Haan A. Temperature effect on the force/velocity relationship of the fresh and fatigued human adductor pollicis muscle. *Pflügers Archiv-European Journal of Physiology.* 2000;440(1):163-170.
112. Brocherie F, Girard O, Pezzoli A, Millet GP. Outdoor exercise performance in ambient heat: Time to overcome challenging factors? *International Journal of Hyperthermia.* 2014;30(8):547-549.
113. Docherty D, Hodgson MJ. The application of postactivation potentiation to elite sport. *International Journal of Sports Physiology and Performance.* 2007;2(4):439-444.
114. Sale D. Postactivation potentiation: Role in performance. *British Journal of Sports Medicine.* 2004;38(4):386-387.
115. Rassier DE, Macintosh BR. Coexistence of potentiation and fatigue in skeletal muscle. *Brazilian Journal of Medical and Biological Research.* 2000;33(5):499-508.
116. Tillin NA, Bishop D. Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. *Sports Medicine (Auckland, NZ).* 2009;39(2):147-166.
117. Hodgson M, Docherty D, Robbins D. Post-activation potentiation: Underlying physiology and implications for motor performance. *Sports Medicine (Auckland, NZ).* 2005;35(7):585-595.

118. Weber KR, Brown LE, Coburn JW, Zinder SM. Acute effects of heavy-load squats on consecutive squat jump performance. *The Journal of Strength and Conditioning Research.* 2008;22(3):726-730.

119. Wallace BJ, Shapiro R, Wallace KL, Abel MG, Symons TB. Muscular and neural contributions to postactivation potentiation. *The Journal of Strength and Conditioning Research.* 2019;33(3):615-625.

120. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Neural adaptation to resistance training: Changes in evoked V-wave and H-reflex responses. *Journal of Applied Physiology.* 2002;92(6):2309-2318.

121. Smith JC, Fry AC. Effects of a ten-second maximum voluntary contraction on regulatory myosin light-chain phosphorylation and dynamic performance measures. *The Journal of Strength and Conditioning Research.* 2007;21(1):73-76.

122. Szczesna D, Zhao J, Jones M, Zhi G, Stull J, Potter JD. Phosphorylation of the regulatory light chains of myosin affects Ca2+ sensitivity of skeletal muscle contraction. *Journal of Applied Physiology.* 2002;92(4):1661-1670.

123. McBride JM, Nimphius S, Erickson TM. The acute effects of heavy-load squats and loaded countermovement jumps on sprint performance. *The Journal of Strength and Conditioning Research.* 2005;19(4):893-897.

124. Sanchez-Sanchez J, Rodriguez A, Petisco C, Ramirez-Campillo R, Martinez C, Nakamura FY. Effects of different post-activation potentiation warm-ups on repeated sprint ability in soccer players from different competitive levels. *Journal of Human Kinetics.* 2018;61(1):189-197.

125. Bevan HR, Cunningham DJ, Tooley EP, Owen NJ, Cook CJ, Kilduff LP. Influence of postactivation potentiation on sprinting performance in professional rugby players. *The Journal of Strength and Conditioning Research.* 2010;24(3):701-705.

126. Clark RA, Bryant AL, Reaburn P. The acute effects of a single set of contrast preloading on a loaded countermovement jump training session. *The Journal of Strength and Conditioning Research.* 2006;20(1):162-166.

127. Kilduff LP, Bevan HR, Kingsley MI, et al. Postactivation potentiation in professional rugby players: Optimal recovery. *The Journal of Strength and Conditioning Research.* 2007;21(4):1134-1138.

128. Evetovich TK, Conley DS, McCawley PF. Postactivation potentiation enhances upper- and lower-body athletic performance in collegiate male and female athletes. *The Journal of Strength and Conditioning Research.* 2015;29(2):336-342.

129. Boullosa D, Del Rosso S, Behm DG, Foster C. Post-activation potentiation (PAP) in endurance sports: A review. In. Vol 18: Routledge; 2018:595-610.

130. Garcia-Pinillos F, Molina-Molina A, Latorre-Roman PA. Impact of an incremental running test on jumping kinematics in endurance runners: Can jumping kinematic explain the post-activation potentiation phenomenon? *Sports Biomechanics.* 2016;15(2):103-115.

131. Garcia-Pinillos F, Soto-Hermoso VM, Latorre-Roman PA. Acute effects of extended interval training on countermovement jump and handgrip strength performance in endurance athletes: Postactivation potentiation. *The Journal of Strength and Conditioning Research.* 2015;29(1):11-21.

132. West DJ, Cunningham DJ, Crewther BT, Cook CJ, Kilduff LP. Influence of ballistic bench press on upper body power output in professional rugby players. *The Journal of Strength and Conditioning Research.* 2013;27(8):2282-2287.

133. Winwood PW, Posthumus LR, Cronin JB, Keogh JW. The acute potentiating effects of heavy sled pulls on sprint performance. *The Journal of Strength and Conditioning Research.* 2016;30(5):1248-1254.

134. Chiu LZ, Salem GJ. Potentiation of vertical jump performance during a snatch pull exercise session. *Journal of Applied Biomechanics.* 2012;28(6):627-635.

135. Seitz LB, Trajano GS, Haff GG. The back squat and the power clean: Elicitation of different degrees of potentiation. *International Journal of Sports Physiology and Performance.* 2014;9(4):643-649.

136. Byrne PJ, Kenny J, O' Rourke B. Acute potentiating effect of depth jumps on sprint performance. *The Journal of Strength and Conditioning Research.* 2014;28(3):610-615.

137. Hilfiker R, Hubner K, Lorenz T, Marti B. Effects of drop jumps added to the warm-up of elite sport athletes with a high capacity for explosive force

development. *The Journal of Strength and Conditioning Research.* 2007;21(2):550-555.

138. Thompsen AG, Kackley T, Palumbo MA, Faigenbaum AD. Acute effects of different warm-up protocols with and without a weighted vest on jumping performance in athletic women. *The Journal of Strength and Conditioning Research.* 2007;21(1):52.

139. Turner AP, Bellhouse S, Kilduff LP, Russell M. Postactivation potentiation of sprint acceleration performance using plyometric exercise. *The Journal of Strength and Conditioning Research.* 2015;29(2):343-350.

140. Scott DJ, Ditroilo M, Marshall PA. Complex training: The effect of exercise selection and training status on postactivation potentiation in rugby league players. *The Journal of Strength and Conditioning Research.* 2017;31(10):2694-2703.

141. Lowery RP, Duncan NM, Loenneke JP, et al. The effects of potentiating stimuli intensity under varying rest periods on vertical jump performance and power. *The Journal of Strength and Conditioning Research.* 2012;26(12):3320-3325.

142. Moir GL, Mergy D, Witmer C, Davis SE. The acute effects of manipulating volume and load of back squats on countermovement vertical jump performance. *The Journal of Strength and Conditioning Research.* 2011;25(6):1486-1491.

143. Higuchi T, Nagami T, Mizuguchi N, Anderson T. The acute and chronic effects of isometric contraction conditioning on baseball bat velocity. *The Journal of Strength and Conditioning Research.* 2013;27(1):216-222.

144. Montoya BS, Brown LE, Coburn JW, Zinder SM. Effect of warm-up with different weighted bats on normal baseball bat velocity. *The Journal of Strength and Conditioning Research.* 2009;23(5):1566-1569.

145. Southard D, Groomer L. Warm-up with baseball bats of varying moments of inertia: Effect on bat velocity and swing pattern. *Research Quarterly for Exercise and Sport.* 2003;74(3):270-276.

146. Szymanski DJ, Beiser EJ, Bassett KE, et al. Effect of various warm-up devices on bat velocity of intercollegiate baseball players. *The Journal of Strength and Conditioning Research.* 2011;25(2):287-292.

147. Ohta Y, Ishii Y, Ikudome S, Nakamoto H. Warm-up with weighted bat and adjustment of upper limb muscle activity in bat swinging under movement correction conditions. *Perceptual and Motor Skills.* 2014;118(1):96-113.
148. DeRenne C, Ho KW, Hetzler RK, Chai DX. Effects of warm-up with various weighted implements on baseball bat swing velocity. *The Journal of Strength and Conditioning Research.* 1992;6(4):214-218.
149. Otsuji T, Abe M, Kinoshita H. After-effects of using a weighted bat on subsequent swing velocity and batters' perceptions of swing velocity and heaviness. *Perceptual and Motor Skills.* 2002;94(1):119-126.
150. Chiu LZ, Fry AC, Weiss LW, Schilling BK, Brown LE, Smith SL. Postactivation potentiation response in athletic and recreationally trained individuals. *The Journal of Strength and Conditioning Research.* 2003;17(4):671-677.
151. Wilson JM, Duncan NM, Marin PJ, et al. Meta-analysis of postactivation potentiation and power: Effects of conditioning activity, volume, gender, rest periods, and training status. *The Journal of Strength and Conditioning Research.* 2013;27(3):854-859.
152. Golas A, Maszczyk A, Zajac A, Mikolajec K, Stastny P. Optimizing post activation potentiation for explosive activities in competitive sports. *Journal of Human Kinetics.* 2016;52(1):95-106.
153. Jo E, Judelson DA, Brown LE, Coburn JW, Dabbs NC. Influence of recovery duration after a potentiating stimulus on muscular power in recreationally trained individuals. *The Journal of Strength and Conditioning Research.* 2010;24(2):343-347.
154. Kilduff LP, Owen N, Bevan H, Bennett M, Kingsley MI, Cunningham D. Influence of recovery time on post-activation potentiation in professional rugby players. *Journal of Sports Sciences.* 2008;26(8):795-802.
155. Gullich A, Schmidtbleicher D. Short-term potentiation of power performance induced by maximal voluntary contractions. Paper presented at: XVth Congress of the International Society of Biomechanics1995.
156. Requena B, Gapeyeva H, Garcia I, Ereline J, Paasuke M. Twitch potentiation after voluntary versus electrically induced isometric

contractions in human knee extensor muscles. *European Journal of Applied Physiology.* 2008;104(3):463-472.

157. Rixon KP, Lamont HS, Bemben MG. Influence of type of muscle contraction, gender, and lifting experience on postactivation potentiation performance. *The Journal of Strength and Conditioning Research.* 2007;21(2):500-505.
158. McMahon S, Jenkins D. Factors affecting the rate of phosphocreatine resynthesis following intense exercise. *Sports Medicine (Auckland, NZ).* 2002;32(12):761-784.
159. Harris RC, Edwards RH, Hultman E, Nordesjo LO, Nylind B, Sahlin K. The time course of phosphorylcreatine resynthesis during recovery of the quadriceps muscle in man. *Pflügers Archiv.* 1976;367(2):137-142.
160. Hamada T, Sale DG, MacDougall JD, Tarnopolsky MA. Postactivation potentiation, fiber type, and twitch contraction time in human knee extensor muscles. *Journal of Applied Physiology.* 2000;88(6):2131-2137.
161. Hamada T, Sale DG, MacDougall JD, Tarnopolsky MA. Interaction of fibre type, potentiation and fatigue in human knee extensor muscles. *Acta Physiologica Scandinavica.* 2003;178(2):165-173.
162. Leyva WD, Wong MA, Brown LE. Resisted and assisted training for sprint speed: A brief review. *Journal of Physical Fitness, Medicine & Treatment in Sports.* 2017;1(1):555554.
163. Ebben WP, Davies JA, Clewien RW. Effect of the degree of hill slope on acute downhill running velocity and acceleration. *The Journal of Strength and Conditioning Research.* 2008;22(3):898-902.
164. Ebben WP. The optimal downhill slope for acute overspeed running. *International Journal of Sports Physiology and Performance.* 2008;3(1):88-93.
165. Upton DE. The effect of assisted and resisted sprint training on acceleration and velocity in Division IA female soccer athletes. *The Journal of Strength and Conditioning Research.* 2011;25(10):2645-2652.
166. Whiteside D, Elliott B, Lay B, Reid M. The effect of racquet swing weight on serve kinematics in elite adolescent female tennis players. *Journal of Science and Medicine in Sport.* 2014;17(1):124-128.

167. Elliott BC, Marshall RN, Noffal GJ. Contributions of upper limb segment rotations during the power serve in tennis. *Journal of Applied Biomechanics.* 1995;11(4):433-442.

168. MacKenzie SJ, Ryan B, Rice A. The influence of clubhead mass on clubhead and golf ball kinematics. *International Journal of Golf Science.* 2015;4(2):136-146.

169. Gilmore SL, Brilla LR, Suprak DN, Chalmers GR, Dahlquist DT. Effect of a high-intensity isometric potentiating warm-up on bat velocity. *The Journal of Strength and Conditioning Research.* 2019;33(1):152-158.

170. Moore RL, Stull JT. Myosin light chain phosphorylation in fast and slow skeletal muscles in situ. *American Journal of Physiology-Cell Physiology.* 1984;247(5 Pt 1):C462-471.

171. Morana C, Perrey S. Time course of postactivation potentiation during intermittent submaximal fatiguing contractions in endurance and power-trained athletes. *The Journal of Strength and Conditioning Research.* 2009;23(5):1456-1464.

172. Badenhausen K. Full list: The world's highest-paid athletes 2018. Forbes Media LLC. https://www.forbes.com/sites/kurtbadenhausen/2018/06/13/full-list-the-worlds-highest-paid-athletes-2018/#774681217d9f. Published 2018. Updated Jun 13, 2018, 08:41am. Accessed 30th May, 2019.

173. Doan BK, Newton RU, Kwon YH, Kraemer WJ. Effects of physical conditioning on intercollegiate golfer performance. *The Journal of Strength and Conditioning Research.* 2006;20(1):62-72.

174. Harper TE, Roberts JR, Jones R. Driver swingweighting: A worthwhile process? *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture.* 2005;219(5):385-393.

175. Gelstx. Gelstx - The new standard in hockey training. https://www.gelstx.com. Published 2019. Accessed 1st June, 2019.

176. Better. F-T. Weighted training bats. https://www.forcetrainbetter.com. Published 2019. Accessed 1st June, 2019.

177. Tennis SV. Tennis power trainer duo pack (racket training weight). https://serveandvolleytennis.com/improve-tennis-skills-with-these-top-10-tennis-training-devices/. Published 2019. Accessed 1st June, 2019.
178. SuperSpeedGolf. SuperSpeed Golf pre-round warm-up. Published 2018. Updated 29th August 2018. Accessed.
179. Comyns TM, Harrison AJ, Hennessy L, Jensen RL. Identifying the optimal resistive load for complex training in male rugby players. *Sports Biomechanics.* 2007;6(1):59-70.
180. Jeffreys I. Warm-up revisited: The ramp method of optimizing warm-ups. *Professional Strength And Conditioning.* 2007;6:12-18.
181. Paradisis GP, Cooke CB. The effects of sprint running training on sloping surfaces. *The Journal of Strength and Conditioning Research.* 2006;20(4):767-777.
182. Moran KA, McGrath T, Marshall BM, Wallace ES. Dynamic stretching and golf swing performance. *International Journal of Sports Medicine.* 2009;30(2):113-118.
183. Langdown BL, Wells JET, Graham S, Bridge MW. Acute effects of different warm-up protocols on highly skilled golfers' drive performance. *Journal of Sports Sciences.* 2019;37(6):656-664.
184. Henry E, Berglund K, Millar L, Locke F. Immediate effects of a dynamic rotation-specific warm-up on X-factor and X-factor stretch in the amateur golfer. *International Journal of Sports Physical Therapy.* 2015;10(7):998-1006.
185. Sorbie GG, Hunter HH, Grace FM, Gu Y, Baker JS, Ugbolue UC. An electromyographic study of the effect of hand grip sizes on forearm muscle activity and golf performance. *Research in Sports Medicine.* 2016;24(3):222-233.
186. Read PJ, Miller SC, Turner AN. The effects of postactivation potentiation on golf club head speed. *The Journal of Strength and Conditioning Research.* 2013;27(6):1579-1582.
187. SuperSpeedGolf. SuperSpeed Golf tour professionals. https://superspeedgolf.com/pages/tour-photos. Published 2019. Accessed 6th June, 2019.

188. SuperSpeedGolf. Phil Mickleson using SuperSpeed warm-up. https://twitter.com/superspeedgolf/status/1007956346942230528?lang=en. Published 2018. Accessed 16th June, 2018.

189. Rosner B. *Fundamentals of biostatistics.* Nelson Education; 2015.

190. Lephart SM, Smoliga JM, Myers JB, Sell TC, Tsai YS. An eight-week golf-specific exercise program improves physical characteristics, swing mechanics, and golf performance in recreational golfers. *The Journal of Strength and Conditioning Research.* 2007;21(3):860-869.

191. Harriss DJ, Macsween A, Atkinson G. Standards for ethics in sport and exercise science research: 2018 update. *International Journal of Sports Medicine.* 2017;38(14):1126-1131.

192. Hireko. Head Weights, Shaft Weights and Balance Points. https://www.hirekogolf.com/head-weights-shaft-weights-and-balance-points-oh-my. Accessed 18th July, 2019.

193. Dempster WT. *Space requirements of the seated operator, geometrical, kinematic, and mechanical aspects of the body with special reference to the limbs.* Michigan State Univ East Lansing;1955.

194. C-Motion. Marker set guidelines. C-Motion. https://www.c-motion.com/v3dwiki/index.php/Marker_Set_Guidelines. Published 2019. Updated 15th August 2017. Accessed 1st June, 2019.

195. Bell AL, Brand RA, Pedersen DR. Prediction of hip joint centre location from external landmarks. *Human Movement Science.* 1989;8(1):3-16.

196. Qualisys. *Golf Performance Module - User Manual.* Sweden 18th December 2017 2017.

197. Knudson D, Bahamonde R. Effect of endpoint conditions on position and velocity near impact in tennis. *Journal of Sports Sciences.* 2001;19(11):839-844.

198. Baker R. Pelvic angles: a mathematically rigorous definition which is consistent with a conventional clinical understanding of the terms. *Gait & Posture.* 2001;13(1):1-6.

199. Smith TB, Hopkins WG. Variability and predictability of finals times of elite rowers. *Medicine and Science in Sports and Exercise.* 2011;43(11):2155-2160.

200. Cross R. Impact of sports balls with striking implements. *Sports Engineering.* 2013;17(1):3-22.

201. Sweeney M, Mills P, Alderson J, Elliott B. The influence of club-head kinematics on early ball flight characteristics in the golf drive. *Sports Biomechanics.* 2013;12(3):247-258.

202. Penner AR. The physics of golf. *Reports on Progress in Physics.* 2003;69:563 - 568.

203. Wallace ES, Otto SR, Nevill A. Ball launch conditions for skilled golfers using drivers of different lengths in an indoor testing facility. *Journal of Sports Sciences.* 2007;25(7):731-737.

204. Sprigings EJ, Neal RJ. An insight into the importance of wrist torque in driving the golfball: A simulation study. *Journal of Applied Biomechanics.* 2000;16(4):356-366.

205. Ball K, Best R. Centre of pressure patterns in the golf swing: Individual-based analysis. *Sports Biomechanics.* 2012;11(2):175-189.

206. Seaman DR, Bulbulian R. A review of back pain in golfers: Etiology and prevention. *Research in Sports Medicine.* 2000;9:169-187.

207. Sinclair J, Hebron J, Taylor PJ. The influence of tester experience on the reliability of 3D kinematic information during running. *Gait Posture.* 2014;40(4):707-711.

208. Masamoto N, Larson R, Gates T, Faigenbaum A. Acute effects of plyometric exercise on maximum squat performance in male athletes. *The Journal of Strength and Conditioning Research.* 2003;17(1):68-71.

209. Higdon NR, Finch WH, Leib D, Dugan EL. Effects of fatigue on golf performance. *Sports Biomechanics.* 2012;11(2):190-196.

210. Seitz LB, de Villarreal ES, Haff GG. The temporal profile of postactivation potentiation is related to strength level. *The Journal of Strength and Conditioning Research.* 2014;28(3):706-715.

211. Seitz LB, Haff GG. Factors modulating post-activation potentiation of jump, sprint, throw, and upper-body ballistic performances: A systematic review with meta-analysis. *Sports Medicine (Auckland, NZ).* 2016;46(2):231-240.

212. Cook CJ, Beaven CM, Kilduff LP. Three weeks of eccentric training combined with overspeed exercises enhances power and running speed performance gains in trained athletes. *The Journal of Strength and Conditioning Research.* 2013;27(5):1280-1286.

213. Sheppard JM, Dingley AA, Janssen I, Spratford W, Chapman DW, Newton RU. The effect of assisted jumping on vertical jump height in high-performance volleyball players. *Journal of Science and Medicine in Sport.* 2011;14(1):85-89.

214. Hayes PR, van Paridon K, French DN, Thomas K, Gordon DA. Development of a simulated round of golf. *International Journal of Sports Physiology and Performance.* 2009;4(4):506-516.

215. Smith M. The role of physiology in the development of golf performance. *Sports Medicine* 2010;40:635-655.

216. Sell TC, Abt JP, Lephart SM. Physical activity-related benefits of walking during golf. Paper presented at: Science and Golf V: Proceedings of the World Scientific Congress of Golf. 2008.

217. Stevenson EJ, Hayes PR, Allison SJ. The effect of a carbohydrate-caffeine sports drink on simulated golf performance. *Applied Physiology, Nutrition, and Metabolism.* 2009;34(4):681-688.

218. R&A. Rules of golf - Pace of play manual. https://www.randa.org/pace-of-play-manual/rules/6-appendices/subrules/3-appendix-c. Published 2019. Accessed 15th June 2019, 2019.

219. Green A. *The biomechanical and physiological predictors of golf drive performance, before and after a hole-to-hole distance walk.* Johannesburg: Faculty of Health Science, University of the Witwatersrand; 2012.

220. Knight CA. Neuromotor issues in the learning and control of golf skill. *Research Quarterly for Exercise and Sport.* 2004;75(1):9-15.

221. Doan BK, Newton RU, Kraemer WJ, Kwon YH, Scheet TP. Salivary cortisol, testosterone, and T/C ratio responses during a 36-hole golf competition. *International Journal of Sports Medicine.* 2007;28(6):470-479.

222. Edholm P, Krustrup P, Randers MB. Half-time re-warm up increases performance capacity in male elite soccer players. *Scandinavian Journal of Medicine and Science in Sports.* 2014;25(1):e40-e49.

223. Lovell R, Midgley A, Barrett S, Carter D, Small K. Effects of different half-time strategies on second half soccer-specific speed, power and dynamic strength. *Scandinavian Journal of Medicine and Science in Sports.* 2013;23(1):105-113.

224. Zois J, Bishop D, Fairweather I, Ball K, Aughey RJ. High-intensity re-warm-ups enhance soccer performance. *International Journal of Sports Medicine.* 2013;34(9):800-805.

225. R&A. Rule of golf - The players equipment. https://www.randa.org/en/rog/2019/rules/the-rules-of-golf/rule-4#4-3a. Published 2019. Accessed 17th June, 2019.

226. Duthie GM, Young WB, Aitken DA. The acute effects of heavy loads on jump squat performance: An evaluation of the complex and contrast methods of power development. *The Journal of Strength and Conditioning Research.* 2002;16(4):530-538.

227. Naruo T, Mizota T. The Influence of Golf Ball Dimples on Aerodynamic Characteristics. In. Vol 722014:780-785.

Appendix 1. Ethics application approval

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Human Research Ethics Committee
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Email:humanethics@waikato.ac.nz

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

15th June 2018

George Wardell
Kim Hèbert-Losier

Dear George

UoW HREC(Health)#2018-35: Over speed training effect on golf swing performance

Thank you for submitting your amended application HREC(Health)#2018-35 for ethical approval.

We are now pleased to provide formal approval for your investigation into whether over speed training improves golf swing performance, involving up to 20 golfers with a handicap of less than 3, participating in 2 (or 3 for validity testing) sessions over a 7-day period, of 2 hours each, under different warm up conditions. You have clarified that you will conduct the research at the Adams Centre for High Performance, and that you will advertise for participants through the Faculty's Web Page. We are unable to approve recruitment via a personal social media account, using the University logo.

Please contact the committee by email (humanethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds (including updating your recruitment processes), quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Regards,

Julie Barbour PhD
Chairperson
University of Waikato Human Research Ethics Committee

Appendix 2. Supplementary figures

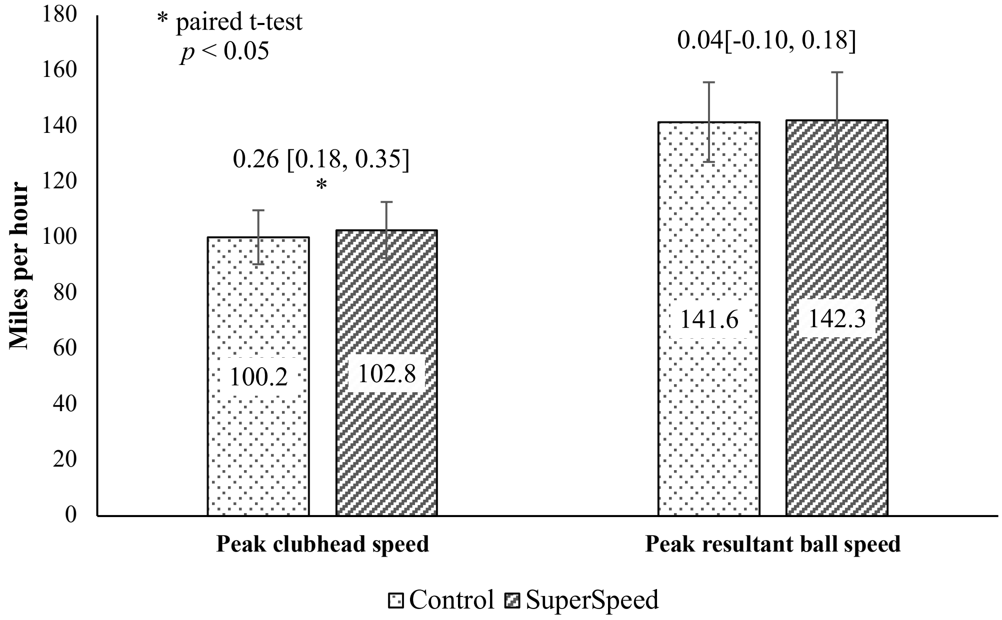

Figure S1. Peak clubhead speed and resultant ball speed (mean) with control and SuperSpeed warm-up protocols in high level amateur golfers (n = 12). Error bars represent standard deviations. Clear and likely effect size and 95% confidence intervals [lower, upper] provided above bars.

Appendix 2 *(continued)*. **Supplementary figures**

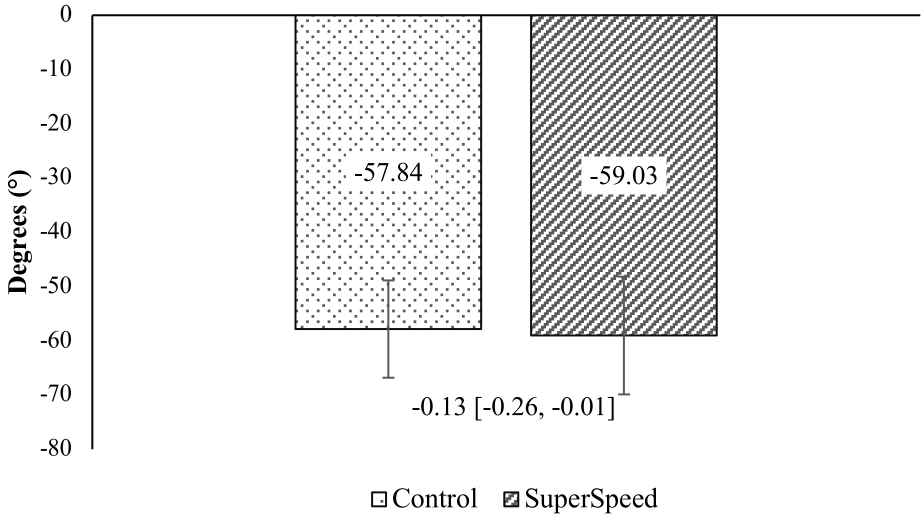

Figure S2. X-factor at top of back swing (mean) with control and SuperSpeed warm-up protocols in high level amateur golfers (n = 12). Error bars represent standard deviations. Clear and likely effect size and 95% confidence intervals [lower, upper] provided below bars.

Appendix 2 *(continued)*. **Supplementary figures**

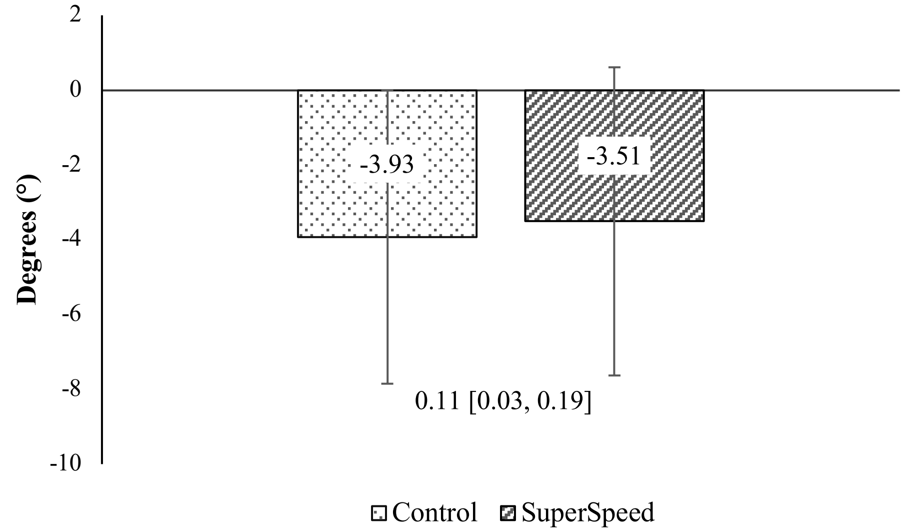

Figure S3. X-factor stretch (mean) with control and SuperSpeed warm-up protocols in high level amateur golfers (n = 12). Error bars represent standard deviations. Clear and likely effect size and 95% confidence intervals [lower, upper] provided below bars.

Appendix 2 *(continued)*. **Supplementary figures**

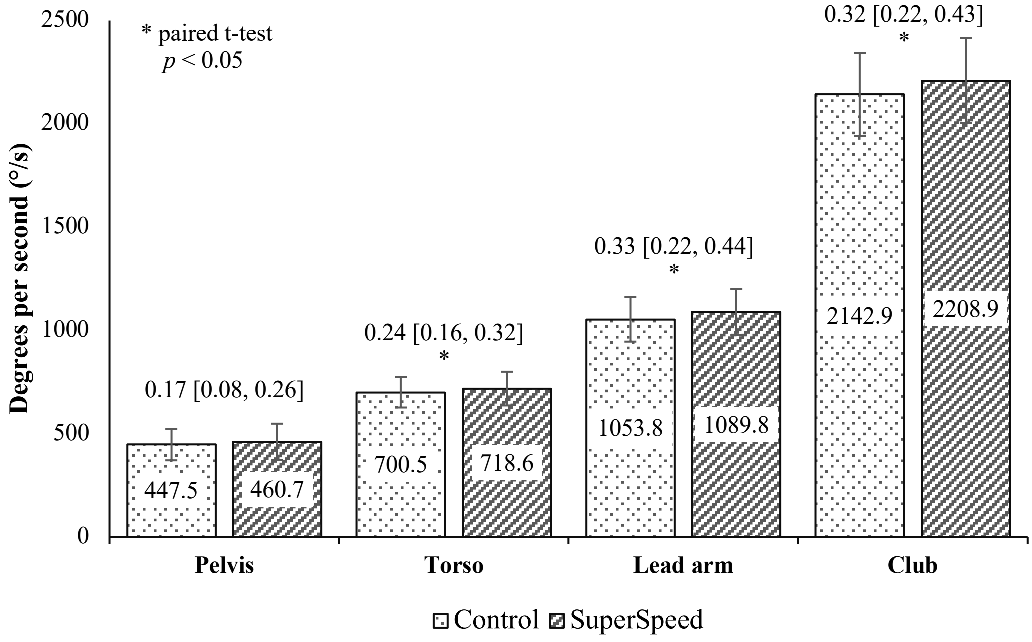

Figure S4. Peak angular velocity parameters (mean) with control and SuperSpeed warm-up protocols in high level amateur golfers (n = 12). Error bars represent standard deviations. Clear and likely effect size and 95% confidence intervals [lower, upper] provided above bars.

Appendix 2 *(continued)*. **Supplementary figures**

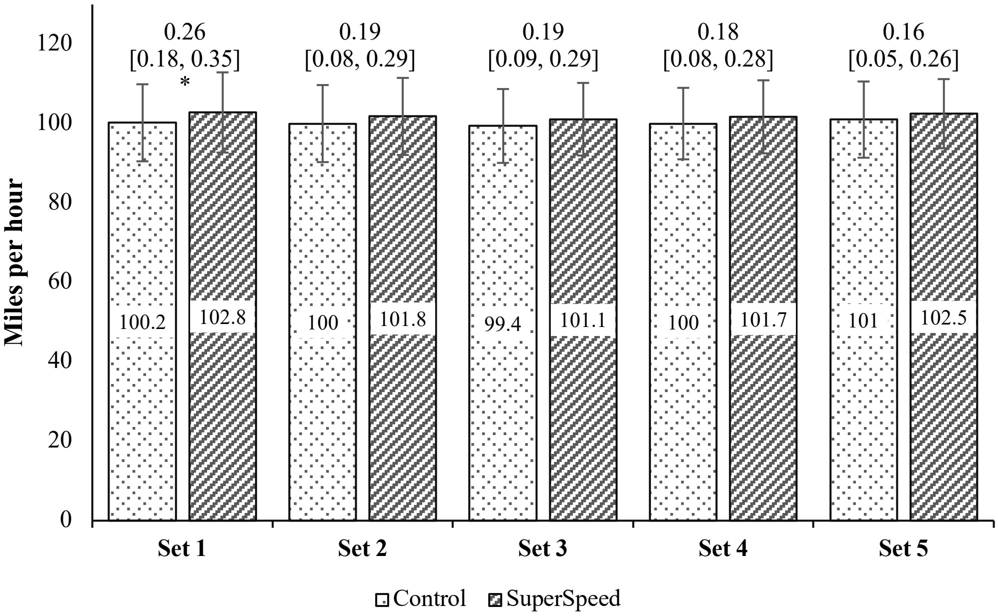

Figure S5. Peak clubhead speed (mean) across sets with control and SuperSpeed warm-up protocols in high level amateur golfers (n = 12). Error bars represent standard deviations. Clear and likely effect size and 95% confidence intervals [lower, upper] provided above bars. * paired t-test $p < 0.05$.

Appendix 2 *(continued)*. **Supplementary figures**

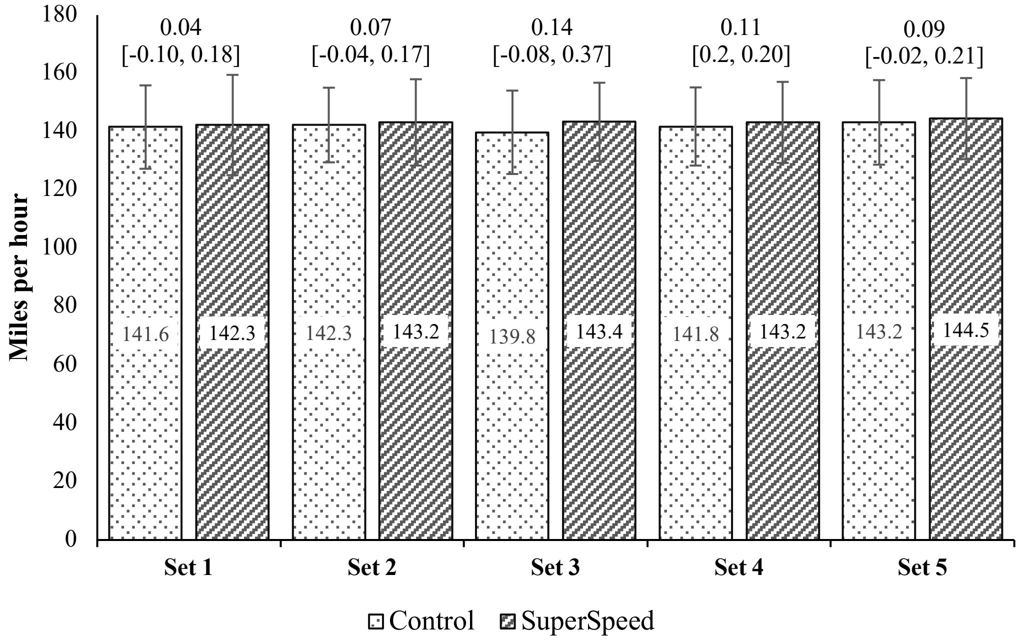

Figure S6. Peak resultant ball speed (mean) across sets with control and SuperSpeed warm-up protocols in high level amateur golfers (n = 12). Error bars represent standard deviations. Clear and likely effect size and 95% confidence intervals [lower, upper] provided above bars.

Appendix 2 *(continued)*. **Supplementary figures**

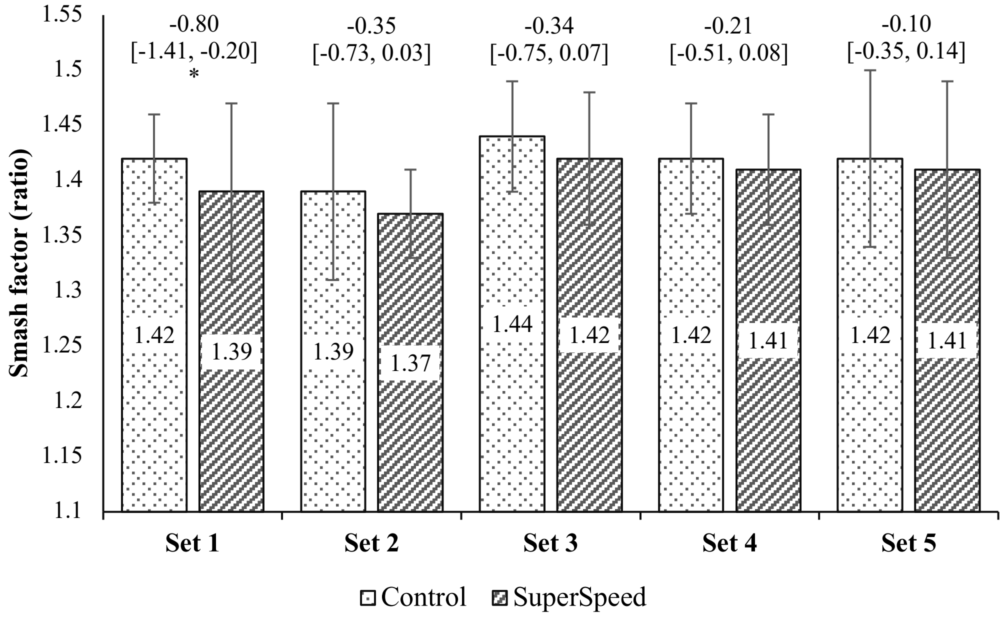

Figure S7. Smash factor (mean) across sets with control and SuperSpeed warm-up protocols in high level amateur golfers (n = 12). Error bars represent standard deviations. Clear and likely effect size and 95% confidence intervals [lower, upper] provided above bars. * paired t-test $p < 0.05$.