Journal of Sports Sciences

The effect of alterations in foot centre of pressure on lower body kinematics during the 5-iron golf swing.

--Manuscript Draft--

Full Title:	The effect of alterations in foot centre of pressure on lower body kinematics during the 5-iron golf swing.
Manuscript Number:	RJSP-2018-0572R2
Article Type:	Original Manuscript
Keywords:	golf biomechanics; foot pressure distribution; Injury; longitudinal intervention
Abstract:	The research aimed to evaluate the effects of an intervention aimed at altering pressure towards the medial aspect of the foot relating to stability mechanisms associated with the golf swing. The hypothesis that by altering the position of the foot pressure, the lower body stabilisation would improve which in turn would enhance weight distribution and underpinning lower body joint kinematics. Eight PGA golf coaches performed five golf swings, recorded using a nine-camera motion analysis system synchronised with two force platforms. Following verbal intervention they performed a further five swings. One participant returned following a one-year intervention programme and performed five additional golf swings to provide a longitudinal case study analysis. There were no changes in golf performance evidenced by the velocity and angle of the club at ball impact. although the one-year intervention significantly changed the percentage of weight experienced at each foot in the final 9% of downswing, which provided an even weight distribution at ball impact. This is a highly relevant finding as it indicates that the foot centre of pressure was central to the base of support and in-line with the centre of mass, indicating significantly increased stability when the centre of mass is near maximal acceleration.
Order of Authors:	Lesley Faux, MSc
	Alison Carlisle, MSc
	John Vickers
	Ceri E Diss, PhD BA(Hons) PGCE Msc
Response to Reviewers:	Reviewer #1: Thank you for reviewing the manuscript and your positive response. Reviewer #2: The majority of my comments have been adequately addressed, however, given the additional information now provided on the coaching sessions for the case study I no longer consider that the case study should be included in the present manuscript. Response: Thank you for your review. We have endeavoured to address all of your queries accurately. Title Suggest changing title to "The effect of alterations in foot centre of pressure on lower body kinematics during the 5-iron golf swing." Response: The title has been changed. Abstract Update abstract within submission portal: While the abstract within the submitted manuscript has been modified to reflect the reviewers comments the abstract section within the submission portal has not been updated. Response: We apologise for not uploading the correct abstract to the submission portal. The correct abstract has now been uploaded. Introduction Similar to my comment on the 1st version of the paper's abstract, I consider the

reference to injury should be removed as this is not related to the aim of the study. "The potential outcomes of the intervention were to decrease the mechanics that underpin injury without decreasing club head velocity and angle at BI." It is unclear what is meant by "decrease the mechanics that underpin injury".

Response: We agree that we can not assess the effects of the intervention on injury. Therefore the sentence has been removed.

Methods
Page 7: "between five and ten swings" - How was the number of swings decided and by who? Did the golfer stop when they had performed 5 'good shots'?

Response: An additional sentence has been included to clarify that the golfer's self-determined that they had performed at least five 'good swings.'

Page 7: Considering the additional information now provided on the coaching sessions "progressive optimal joint function movements and strength training relating specifically to the golf swing" I consider that the case study should be removed from the manuscript. Based on the first version of the manuscript I had assumed the additional coaching sessions solely consisted of verbal instruction on the technique adjustment as the manuscript stated, "The case study golfer received 30 coaching sessions over a one-year programme where the changes in foot pressure throughout their swing was reiterated". However, the additional information now provided shows that these sessions were different to the session performed with the 8 golfers and therefore it is not appropriate to include the case study in this manuscript. I suggest the case study is written up as a separate manuscript.

Response: In the revised manuscript the statement that the participant received 'optimal joint function movements and strength training', which was provided by the golf specialist, is misleading. The specialist considered that the visual and verbal instructions provided to the golfer during intervention sessions could be described as coaching functional movement and strength. The terms have been removed and the text now clarifies that the long-term intervention sessions mirrored the immediate intervention, which it did.

I queried if ball velocity had been measured in the 1st version of the manuscript and the authors response was "The ball velocity was reported but the limitations associated with its measurement has been reported in the limitations.", however, I don't see ball velocity reported in the results section or discussed within the limitations.

Response: Apologise this is incorrect. We did not report the ball velocity. Instead we have reported the club head velocity at ball impact but have addressed, in the limitations, that the low sampling frequency can affect the accuracy of such a measure.

Table 1

		IMMEDIATE INTERVENTION (n=8)		LONGITUDINAL INTERVENTION (n = 1)			
		Mean (SD)		Mean (SD)		Difference (%)	Effect size (Hedge's g)
		Pre-	Post-	Pre-	One year		
TRAIL ANKLE							
ADD	Dorsi-/Plantar-flexion	13.1 (4.8)	13.9 (4.6)	13.9 (0.8)	11.6 (0.6)	-17	3.26 ^
	Inversion/Eversion	2.0 (1.7)	2.7 (2.4)	1.0 (0.3)	3.1 (0.1)	210	9.39 ^
	Rotation	-8.5 (6.2)	-10.6 (8.9)	-5.9 (1.6)	-21.8 (0.5)	269	13.42 ^
ToBS	Dorsi-/Plantar-flexion	5.1 (4.0) *	7.0 (3.9) *	4.3 (1.5)	3.3 (0.7)	-23	0.86
	Inversion/Eversion	-4.7 (1.7) *	-3.3 (1.9) *	-5.4 (0.3)	-0.3 (0.3)	-94	17.00 ^
	Rotation	16.2 (7.3) *	11.4 (8.6) *	27.3 (1.2)	0.6 (2.2)	-98	15.07 ^
BI	Dorsi-/Plantar-flexion	11.8 (8.0)	14.2 (4.8)	14.4 (0.8)	12.5 (1.3)	-13	1.76 ^
	Inversion/Eversion	7.3 (2.3)	7.3 (3.6)	4.7 (0.2)	6.0 (1.1)	28	1.65 ^
	Rotation	-27.5 (5.7)	-25.4 (7.9)	-24.8 (0.8)	-36.4 (4.6)	47	3.52 ^
LEAD ANKLE							
ADD	Dorsi-/Plantar-flexion	9.5 (2.1)	10.1 (1.9)	8.1 (0.7)	9.4 (0.8)	16	1.73 ^

	Inversion/Eversion	3.1 (1.8)	3.3 (2.0)	0.8 (0.2)	1.4 (0.2)	75	3.00 ^
	Rotation	-13.7 (7.0)	-14.6 (8.5)	-4.0 (1.2)	-7.2 (1.3)	80	2.56 ^
ToBS	Dorsi-/Plantar-flexion	19.9 (6.7)	21.1 (5.7)	9.9 (1.7)	20.1 (0.2)	103	8.43 ^
	Inversion/Eversion	8.0 (2.3)	8.1 (3.4)	6.9 (0.4)	6.8 (0.4)	-1	0.25
	Rotation	-32.6 (8.0)	-31.6 (9.2)	-33.5 (1.2)	-35.1 (1.4)	5	1.23
BI	Dorsi-/Plantar-flexion	7.6 (5.8)	7.7 (5.4)	7.3 (0.9)	5.2 (1.8)	-29	1.48 ^
	Inversion/Eversion	-0.2 (2.2) *	0.9 (2.2) *	-0.7 (0.2)	1.3 (0.7)	-286	3.88 ^
	Rotation	-0.6 (8.9) *	-5.2 (8.4) *	4.2 (0.9)	-6.6 (3.9)	-257	3.82 ^
TRAIL KNEE							
ADD	Varus/Valgus	-0.3 (5.1)	-1.4 (5.2)	-0.8 (0.4)	-3.4 (0.4)	325	6.50 ^
ToBS	Varus/Valgus	-5.4 (4.4) *	-6.9 (4.2) *	-4.6 (0.6)	-11.7 (1.0)	154	8.61 ^
BI	Varus/Valgus	-1.6 (6.5)	-0.5 (4.2)	-0.3 (0.5)	-5.4 (0.7)	1700	8.38 ^
LEAD KNEE							
ToBS	Varus/Valgus	15.3 (8.4) *	13.2 (8.3) *	18.2 (1.2)	6.5 (1.1)	-64	10.16 ^
BI	Varus/Valgus	3.9 (4.8) *	2.0 (4.6) *	9.2 (1.0)	-5.6 (1.8)	-161	10.16 ^
TRAIL HIP							

ADD	Rotation	-2.6 (9.1)	-2.4 (9.4)	3.4 (0.4)	-0.8 (0.6)	-124	8.24 ^
ToBS	Rotation	5.0 (9.1)	3.8 (9.3)	15.7 (0.3)	3.7 (0.6)	-76	25.29 ^
LEAD HIP							
ToBS	Rotation	-5.6 (12.0)	-6.2 (11.6)	2.4 (0.6)	-15.3 (0.8)	-738	25.04 ^
BI	Rotation	4.4 (12.8)	6.0 (13.3)	16.9 (1.2)	-5.3 (1.2)	-131	18.50 ^

The effect of alterations in foot centre of pressure on lower body kinematics during the 5-iron golf swing.

Running title: Weight distribution during the golf swing

The effect of alterations in foot centre of pressure on lower body kinematics during the 5-iron golf swing.

Abstract

The research aimed to evaluate the effects of an intervention aimed at altering pressure towards the medial aspect of the foot relating to stability mechanisms associated with the golf swing. The hypothesis that by altering the position of the foot pressure, the lower body stabilisation would improve which in turn would enhance weight distribution and underpinning lower body joint kinematics. Eight PGA golf coaches performed five golf swings, recorded using a nine-camera motion analysis system synchronised with two force platforms. Following verbal intervention they performed a further five swings. One participant returned following a one-year intervention programme and performed five additional golf swings to provide a longitudinal case study analysis. There were no changes in golf performance evidenced by the velocity and angle of the club at ball impact. although the one-year intervention significantly changed the percentage of weight experienced at each foot in the final 9% of downswing, which provided an even weight distribution at ball impact. This is a highly relevant finding as it indicates that the foot centre of pressure was central to the base of support and in-line with the centre of mass, indicating significantly increased stability when the centre of mass is near maximal acceleration.

Keywords: golf biomechanics; foot pressure distribution; injury; longitudinal intervention

Introduction

The golf swing is a whole body multi-joint movement utilised by the golfer to propel a golf ball in a pre-determined direction (Maddalozzo, 1987). There is an integral relationship through the entire movement, from the golfers' address (ADD) to top of the back swing (ToBS) and returning the club to ball impact (BI) as illustrated in Figure 1. The swing's momentum transfers through the kinetic chain from the feet, pelvis, trunk, arms and club, finally connecting with the golf ball, resulting in ball projection (McHardy & Pollard, 2005). To generate a repeatable efficient physical movement that tolerates alternating situations during competitive play a golfer requires a co-ordination of specific body components to activate in the correct sequence (Abernethy, Neal, Moran, & Parker, 1990; Neal et al., 2008). The efficiency of the golfer is dependent on maintaining a stable centre of mass (CoM). Consequently, the golfer aims to limit the medio-lateral, anterior-posterior and vertical movement of the CoM, whilst generating their maximal change in momentum during the swing to propel the ball over horizontal distances of approximately 230m (Hume, Keogh & Reid, 2005).

****Figure 1 near here****

Previous research has implicated that controlled movement of the CoM, ranges of angular motion (RoM) at the hip, knee and ankle joints, lower body internal rotation moments and efficient weight-shift patterns (i.e. movement of the centre of pressure within the base of support), all have a role in determining the golfers skill level (Gatt, Pavol, Parker, & Grabiner, 1998; Hume, Keogh, & Reid, 2005; Lephart, Smoliga, Myers, Sell, & Tsai, 2007). Farrally et al. (2003) suggested that swing consistency is compromised when there is excessive movement of CoM during the backward and downward swing. Highly skilled players display a similar kinematic sequence and have sufficient stability to control the movement of the CoM by holding a correctly aligned spine angle whilst minimising the displacement of the pelvis (Tinmark, Hellström, Halvorsen, & Thorstensson, 2010). Mayer et al. (2008) reported that increased ball velocity can be achieved by increased torso-pelvic separation whilst maintain a pelvic stability. Faster BI velocities have been associated with a stable pelvic rotation at the end of the backswing, increased trunk rotation velocity during downswing, and high acceleration of the trunk segment through to impact (Chu, Sell, & Lephart, 2010; Hume et al., 2005).

An understanding of the distribution of forces between each foot during the swing as fundamental for achieving optimal biomechanics that contribute to peak performance without incurring injury (Barrentine, Fleisig, Johnson, & Woolley, 1994). Furthermore, correct distal to proximal sequence and coordination of lower body segments provides efficient energy transfer and power at BI whilst minimising the potential for injury (Hellström, 2009). The summation of forces principle defined as ‘the increase of velocity at the most distal segment’ (Hume et al., 2005), combined with correct and timely weight-shift transfer is integral to the swing. Lack of correct and consistent weight-shift prevents significant transfer of forces to the club-head, ultimately inhibiting the ‘squaring’ or optimal angle of the club-head to the ball at impact. Highly skilled golfers employ a fast, common weight shift compared to the erratic patterns of novice golfers (Barrentine et al., 1994). The desired maximal changes in momentum and the weight shift that occurs during the backswing to the downswing renders the body vulnerable to a myriad of injuries.

Both pronation and supination of the foot have been shown to be essential for momentum and neutral, optimal balance when standing. When sufficient pressure is on the medial portion of the calcaneus (medial tuberosity) and the distal head of the first metatarsal of the foot, the mid tarsal joint unlocks resulting in a flexible and adjustable dorsal foot surface which is key to maintaining balance (Astrom & Anlidson, 1995). When this does not occur, the foot may not adequately adapt, increasing the requirement on surrounding musculoskeletal structures to maintain postural stability, and subsequently causing compensation in other areas resulting in unnecessary, excessive movement of the lower body (Winter, 1995). Translating this key principal of balance and stability to the golf swing, Richards, Farrell, Kent, & Kraft, 1985 found a more efficient and rapid weight-shift on the lead foot after adjustments to the centre of pressure to various points on the foot leading to an increase to the base of support during downswing and hence stability. Cote, Brunet, Gansneder, & Shultz (2005) demonstrated that when the foot is slightly inverted, partial medial contact is lost with the ground, and it is not possible to subsequently control the weight-shift pattern effectively. Therefore, it is anticipated that when this foundation of foot pressure distribution is applied correctly, there will be a greater control of CoM motion due to the enhanced stability and this was the rationale for conducting the study. Using this premise an intervention to adjust medial pressure on each foot during the golf swing was developed with the aim of quantifying the effects of this intervention on lower body biomechanics. Initially the immediate effects of the pressure intervention were examined on a group of experienced golfers. Group analysis on the golf swing, which is inherently varied (Hume et al., 2005; McNitt-Gray, Munaretto, Zaferiou, Requejo, & Flashner, 2013), provides a trend from the biomechanical data sets examined (Ball & Best, 2012) whereas a case study approach bridges the science-practice gap providing application to individual golfers (Halperin, 2018). Hence, the long term outcomes of the intervention for one single case study golfer was conducted.

The intervention aimed to increase pressure medially to the forefoot and heel of the trail foot during the backswing and equally on the lead foot during the downswing. Therefore, both the immediate and longitudinal intervention examined the differences in ground reaction forces (GRF) and lower body angles and hypothesised that the intervention would induce the following changes:

1. An even weight distribution in the latter part of the downswing, evidenced by the distribution of the GRF (%GRF), increasing the body's stability with the CoP being central to the base of support at BI.
2. Alter the position of the subtalar joints and the ankle angles in all three planes.
3. Decreased trail (knee) valgus angles during both the backswing and downswing, and decreased lead (knee) valgus during the downswing which will affect knee angles in the frontal plane.
4. Minimise internal hip rotation in the trail side during the backswing and the lead side during the downswing to infer greater stabilisation of the knee (Powers, 2010).

Methods

Eight male participants (mean (±SD)): height 1.81 m (±0.05); mass 89.13 kg (±6.66)); age 45 years (±6) were recruited to the study with one of the golfers returning to the study one year later. All participants were professional golf association (PGA) qualified coaches with a zero handicap. The University's Ethics Board granted approval and written informed consent was obtained from each participant. Each of the participants used the same dedicated 5-iron club throughout the duration of the study. The club's sole purpose was to reduce variability in this research and it was not used in any other capacity. They wore their own golf shoes standing on two uncovered force plates located side by side; the researcher adjusted the tee-off position to suit their stance. Participants performed multiple practice swings for self-determined familiarisation within the laboratory environment. After familiarisation, each participant then performed between five and ten swings with maximum velocity at BI. The number of swings were self-determined by the golfers where they ensured that they had performed at least five 'good swings'. The participants aimed the ball into a net 6m from the tee-off position. The participants then received a verbal intervention and were instructed to increase foot pressure on to the medial portion of the ball and heel of the foot, increasing eversion in both backswing and downswing. Specifically, just prior to the initiation of the backswing they were asked to apply pressure vertically onto the medial part of the trail foot (putting the foot into slight pronation), then prior to initiation of the downswing the instruction was to apply pressure vertically on to the medial portion of the lead foot. The verbal information was the same for each participant and all adjusted their technique in accordance with the feedback. The feedback aimed to mimic a real-life coaching session and therefore each participant was provided with a visual demonstration of the technique coupled with verbal instruction in a language they would understand. Following this, the participants performed a further five to ten golf swings at a maximum velocity at BI. The case study golfer received 30 coaching sessions over a one-year programme, typically two or three times per month. The case study intervention sessions comprised of the visual demonstration of the technique coupled with verbal instruction on the changes on foot pressure, which were delivered by the lead researcher, whom is a golf specialist. Returning to the laboratory after one year the golfer performed five to ten swings at a maximal velocity at BI. The laboratory setup was identical one year later for the case study and the participant wore the same shoes. Five golf swings were analysed for each condition (pre and post immediate intervention, pre and post long term intervention) which were selected by the golfer's self-determined assessment of a 'good shot'.

All golf swings were recorded with a nine camera (sample rate: 100 Hz) infra-red Vicon MXF20 motion analysis system (Vicon Motion Systems Ltd, UK) synchronised with two 0.6 x 0.4m Kistler (sample rate: 1000 Hz) 9281CA force plates (Kistler Instruments Ltd, UK). Sixteen retro-reflective markers were placed on precise anatomical landmarks of the lower body according to the protocol (Davis, Ounpuu, Tyburski, & Gage, 1991). There were an additional three markers placed on the golf club (top of the shaft just below handgrip, mid-shaft and club head) and reflective tape was wrapped around the golf ball to identify the time of BI. The cameras were up-graded to a 12 camera system when the golfer returned after one year.

Data was processed using Nexus version 2 (Vicon Motion Systems Ltd, UK). A 4th order Butterworth filter, with a cut-off frequency of 6Hz was applied to the coordinate trajectories and a cut-off frequency of 30 Hz was applied to the force data. Three-dimension kinematic and kinetic measures were calculated for lower body with the Vicon Plug-in-Gait model which uses the Euler angle theorem and standard inverse dynamics. The time-point prior to movement of the golf club-head defined ADD. The time-point of ToBS was the transition between club head anti-clockwise to a clockwise motion. The time-point of BI was the frame nearest to club-ball contact determined visually; the club and ball were both visible to the camera system. Backswing and downswing phases are illustrated in Figure 1. The velocity and angle of the club head at BI were determined. The % differences in lower body angles following the intervention were reported. The trail and lead angles in all three planes for the ankle, frontal plane for the knee and transverse plane for the hip were examined. The resultant GRF was determined and reported as a % of the golfers' body weight for the trail and lead sides. Matlab version 2013a (Mathworks Inc., Massachusetts, USA) was used to time normalise the angular and GRF waveform data to 100% for the two phases of the golf swing for each trial. From the pre- and post-intervention sessions (immediate and longitudinal), means and standard deviation (SD) were calculated, from the five swings where their BI velocity was maximal. For the immediate intervention analysis group means (SD) were determined for each measure.

The Shapiro-Wilk statistical test for normal distribution revealed that all measures were normally distributed for each time point across both phases. Cohen's d was calculated and corrected for a small population size using hedges g and reported the effect size (*ES*) in the for the difference in club head velocity and angle at BI.

All waveform data were analysed using the statistical parametric mapping (SPM) technique with paired sample t-test. SPM was designed especially for continuous field analysis (Penny, Friston, Ashburner, Kiebel, & Nichols, 2011) and constructs images that lie in the original, biomechanically meaningful sampling space (Pataky, 2010). Open-source one-dimensional package for Matlab (spm1d version M.0.3.1 (2015.08.28)) was used in the analysis and the scalar test statistic SPM*{t}* was computed at each point in the time series as described previously (Robinson, Donnelly, Tsao, & Vanrenterghem, 2013).

Results

Following the immediate intervention the mean (SD) club head velocity at BI for the group changed from 31.02 $m \cdot s^{-1}$ (1.27) to 30.63 $m \cdot s^{-1}$ (1.84), (difference = -1.26 % (*ES* = 0.23) with an angle change from 7.47^{o} (1.69) to 6.62^{o} (3.22) (difference = -7.65%, *ES* = 0.22). Following the longitudinal intervention the mean (SD) club head velocity at BI changed from 31.22 $m \cdot s^{-1}$ (0.51) to 31.39 $m \cdot s^{-1}$ (0.44), (difference = 0.54 %, *ES* = 0.32) with an angle change from 7.95^{o}

(1.36) to 1.69^{o} (8.86) (difference -14.09%, *ES* = 0.53).

It was hypothesised that the intervention would induce an even weight distribution in the latter part of the downswing, evidenced by the %GRF distribution.

****Figure 2 near here****

Figure 2 illustrates the SPM analysis, which revealed no significant differences in any waveform data except for the lead side following the longitudinal intervention for the case study golfer ($\alpha = 0.05$, $t^* = 6.047$, $p = 0.015$) where significant differences occurred from 91% of the downswing up to BI (equating to 0.26s before impact).

****Figures 3-5 near here****

Figures 3 to 5 examine the backswing and downswing kinematic waveforms and significantly different portions in the curves are indicated by the shaded areas from the SPM analysis. Notably, significant changes in the angles examined during the backswing and downswing phases following the longitudinal intervention whereas limited significant changes in such measures following the immediate intervention.

Discussion

The biomechanical consequences following a verbal instruction to alter foot pressure during the golf swing was examined for a group of golfers with a zero handicap. To explore the individual long term mechanical effects the intervention was implement over a one year training programme for a single golfer. The altered foot pressure aimed to alter the body weight distribtion and specific lower body joint angles that are deemed to underpin injury without an effect on club head velocity and angle at BI.

Small changes in club head velocity at BI were reported for all golfers. However following a one year intervention programme for a single golfer the angle of the club at BI showed a change to a slightly flatter position (by 1^o) which would effect the range and trajectory path of the ball, although there was a slight increase in velocity (*ES* = 0.53). The underpinning biomechanics as a response to the altered foot pressure were examined particularly the effects of the longitudinal intervention, in detail.

Initially hypothesised that an even weight distribution in the latter part of the downswing evidenced by the distribution of the GRF (%GRF) would occur. Figure 2 illustrates that for the case study golfer there were changes in the weight distribution which were significant ($\alpha = 0.05$, $t^* = 6.047$, $p = 0.015$) for the lead leg in the latter part of the downswing. At BI the weight distribution between the lead and trial sides were approximately 50% compared previously to a 60-40% divide, respectively. Such changes were not detected following the immediate intervention. This was a highly relevant finding since the centre of pressure was central to the base of support and hence in-line with the CoM at BI increasing stability at a crucial time during the golf swing. Improvements in stability can minimise variability of multiple golf swings during a game. Traditionally the recommendation was that 75 to 80% of the body weight should be on the lead leg (Stover & Mallon, 1992) at and after BI with a consequence of a reduction in stability and increased variability. However, a review on knee injury literature revealed that an intervention that incorporates pelvic stability aids knee rehabilitation and injury prevention (Powers, 2010). Also, it was reported that low variation improves the accuracy and reliability in the task outcomes i.e. the club head velocity and shot accuracy of the golfer's performance (Knight, 2004).

At ADD, the trail and lead ankle angles changed in all three planes for the case study golfer while the initial study participants' experienced limited changes. In addition, alterations in the angular data sets also occurred during the backswing. Most notably as the club moved to ToBS the trail ankle was in a tri-planar neutral position evidenced by zero rotation and eversion angles along with limited dorsi-flexion. Such a position improves foot-ground interface stability during the transition from backswing to downswing, which is presently a desired position to maximise the change in angular momentum (clockwise to anti-clockwise). Stable foot-ground stability initiates correct movement at the shoulders and transferred further along the kinetic chain (Marshall & McNair, 2013). During the downswing up to BI, the significant increase in trail ankle external rotation could be considered problematic. Previously, limiting ankle movement in the transverse plane has been reported in order to prevent injury but during walking, rotations of up to 15^{o} have produced a stable foot position whilst the lower leg rotates. The external rotation on the downswing was severe (36^{o}) and a negative outcome. The aim to maintain a foot flat position, with a neutral centre of pressure, could have caused such injury inducing angular motion.

A significant increase in lead ankle dorsi-flexion towards the later stages of the backswing and the initial stages of the downswing enabled a reduction in lead knee varus positioning the knee closer to neutral by approximately 12^{o} compared to prior the intervention (Basnett et al., 2013). Therefore the lead ankle coupled with the trail improved the stability of the golfer at the crucial temporal part of the golf swing. The outcomes of the changes in the ankle joint kinematics partially supported our expected findings.

The knee joint was examined for varus/valgus angles following the theorised changes of improved knee alignment in the frontal plane. A negative consequence of the intervention was the increased valgus for the trail knee from 40% of the backswing through to BI for the case study golfer and during the final 20% of the backswing for the group (immediate intervention) golfers. For the lead knee during the downswing there was a significant reduction in the varus angle with the knee moving into minimal valgus at BI. The intervention, to some extent, in the frontal plane at BI for the lead knee has improved the desired alignment. The slight valgus position at BI does increase the adductor moments but the modern swing aims for near knee alignment at BI for the transmission of the torque and forces passing through the centre of the knee joint (Marshall & McNair, 2013).

The internal rotation of the trail hip during the backswing significantly reduced (~60%) thereby supporting our theorised changes. The improved neutral position of the trail hip was a direct result of the increased valgus at the knee enabling the shoulders to provide the greatest contribution to the torque on the downswing (Gluck, Bendo, & Spivak, 2008). Previously the lead hip was internally rotated during the downswing and the intervention caused a significant change in hip rotation where the joint was externally rotated at the ToBS by 15.3^{o}. During the downswing the lead hip reduced the extent of external rotation however such an angular motion decreases the expected stability in this joint. Therefore, the predicted outcomes of reduction in internal hip rotation was partially accepted.

Conclusions drawn from this project could be criticised through limitations that present from a relatively small sample size of eight participants in the immediate intervention. The case study where one participant underwent specific training over a longer period was incorporated into the study to overcome this. However, research sample of indiscernible margins that separate highly skilled golfers, can also be a more effective representation and valid rationale using a small sample size, helping to increase statistical power. The authors acknowledge the limitation in equipment as the sampling frequency of the cameras was lower than ideal; furthermore, the ball tracking was not plausible within the field of view and the available technology.

Conclusion

Immediate intervention of a change in centre of pressure during the gold swing provided insight on the potential long term changes that can occur in GRF distribution and ankle, knee and hip joint angles that are associated with injury. The longitudinal one-year intervention programme caused a slight increased club head velocity (*ES* = 0.32) and a flatter angle of the club at BI (*ES* = 0.53). However, there was a significantly improved weight distribution particularly in the last 10% of the downswing up to BI, which enhanced lower body stability and supports our hypothesis. Simultaneously the neutral position of the trail ankle joint in the transverse and frontal planes also enhanced stability at BI, although the hypothesised changes in all ankle angles during the swing were not observed. Lead knee varus reduction at the top of the backswing and the first 20% of the downswing improved the alignment of the ankle, knee and hip which agrees with the hypothesised reduction in lead knee valgus. The hypothsised changes in hip rotation were partially accepted. The application of medial foot pressure caused a significant reduction in hip rotation for the trail leg at address and the final 50% of the backswing which would enhance the torque generated by the trunk on the downswing as the body segment moves from internal rotation to external rotation up to BI. The range of rotation at the lead hip was not excessive which has been reported to be important in the avoidance of labral pathology. Finally, this intervention demonstrated adjustments of foot pressure maybe more effective than the traditional pelvic adjustments in improving a golfer’s lower body stability.

References

Abernethy, B., Neal, R. J., Moran, M. J., & Parker, A. W. (1990). (1990). Expert-novice differences in muscle activity during the golf swing. Paper presented at the *Science and Golf. Proceedings of the First World Scientific Congress of Golf,* St Andrews (UK). 54-60.

Astrom, M., & Anlidson, T. M. D. (1995). Alignment and joint motion in the normal foot. *Orthop Sports Phys Ther, 22*(5), 216-222.

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

Barrentine, S., Fleisig, G., Johnson, H., & Woolley, T. (1994). Ground reaction forces and torques of professional and amateur golfers. Paper presented at the *Science and Golf II. Proceedings of the World Scientific Congress of Golf,* 33-39.

Basnett, C. R., Hanish, M. J., Wheeler, T. J., Miriovsky, D. J., Danielson, E. L., Barr, J., & Grindstaff, T. L. (2013). Ankle dorsiflexion range of motion influences dynamic balance in individuals with chronic ankle instability. *International Journal of Sports Physical Therapy, 8*(2)

Chu, Y., Sell, T. C., & Lephart, S. M. (2010). The relationship between biomechanical variables and driving performance during the golf swing. *Journal of Sports Sciences, 28*(11), 1251-1259.

Cote, K., Brunet, M., Gansneder, B., & Shultz, S. (2005). Effects of pronated and supinated foot postures on static and dynamic postural stability. *J Athl Train*, *40*(1), 41-46.

Davis, R. B., Ounpuu, S., Tyburski, D., & Gage, J. R. (1991). A gait analysis data collection and reduction technique. *Human Movement Science, 10*(5), 575-587.

Farrally, M., Cochran, A., Crews, D., Hurdzan, M., Price, R., Snow, J., & Thomas, P. (2003). Golf science research at the beginning of the twenty-first century. *Journal of Sports Sciences, 21*(9), 753-765.

Gatt, C. J.,Jr, Pavol, M. J., Parker, R. D., & Grabiner, M. D. (1998). Three-dimensional knee joint kinetics during a golf swing. influences of skill level and footwear. *The American Journal of Sports Medicine, 26*(2), 285-294.

Gluck, G. S., Bendo, J. A., & Spivak, J. M. (2008). The lumbar spine and low back pain in golf: A literature review of swing biomechanics and injury prevention. *The Spine Journal, 8*(5), 778-788.

Halperin, I. (2018). Case Studies in Exercise and Sport Sciences: A Powerful Tool to Bridge the Science-Practice Gap. *International journal of sports physiology and performance*, 1-9.

Hellström, J. (2009). Competitive elite golf. *Sports Medicine, 39*(9), 723-741.

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

Knight, C. A. (2004). Neuromotor issues in the learning and control of golf skill. *Research Quarterly for Exercise and Sport, 75*(1), 9-15.

Lephart, S. M., Smoliga, J. M., Myers, J. B., Sell, T. C., & Tsai, Y. S. (2007). An eight-week golf-specific exercise program improves physical characteristics, swing mechanics, and golf performance in recreational golfers. *Journal of Strength and Conditioning Research/National Strength & Conditioning Association, 21*(3), 860-869. doi:R-20606 [pii]

Maddalozzo, G. J. (1987). SPORTS PERFORMANCE SERIES: An anatomical and biomechanical analysis of the full golf swing. *Strength & Conditioning Journal, 9*(4), 6-9.

Marshall, R. N., & McNair, P. J. (2013). Biomechanical risk factors and mechanisms of knee injury in golfers. *Sports Biomechanics, 12*(3), 221-230.

McHardy, A., & Pollard, H. (2005). Muscle activity during the golf swing. *British Journal of Sports Medicine, 39*(11), 799-804; discussion 799-804. doi:39/11/799 [pii]

McNitt-Gray, J., Munaretto, J., Zaferiou, A., Requejo, P., & Flashner, H. (2013). Regulation of reaction forces during the golf swing. *Sports Biomechanics, 12*(2), 121-131.

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

Neal, R., Lumsden, R., Holland, M., Mason, B., Crews, D., & Lutz, R. (2008). Segment interactions: Sequencing and timing in the downswing. Paper presented at the *Science and Golf V: Proceedings of the World Scientific Congress of Golf,* 21-29.

Pataky, T. C. (2010). Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *Journal of Biomechanics, 43*(10), 1976-1982.

Penny, W. D., Friston, K. J., Ashburner, J. T., Kiebel, S. J., & Nichols, T. E. (2011). *Statistical parametric mapping: The analysis of functional brain images* Academic press.

Powers, C. M. (2010). The influence of abnormal hip mechanics on knee injury: A biomechanical perspective. *Journal of Orthopaedic & Sports Physical Therapy, 40*(2), 42-51.

Richards, J., Farrell, M., Kent, J., & Kraft, R. (1985). Weight transfer patterns during the golf swing. *Research Quarterly for Exercise and Sport, 56*(4), 361-365.

Robinson, M. A., Donnelly, C. J., Tsao, J., & Vanrenterghem, J. (2013). Impact of knee modeling approach on indicators and classification of ACL injury risk. *Medicine and Science in Sports and Exercise, 46,* 1269-1276.

Stover, C., & Mallon, W. (1992). Golf injuries: Treating the play to treat the player. *J Musculoskelet Med, ,* 55-72.

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

Winter, D. A. (1995). Human balance and posture control during standing and walking. *Gait & Posture*, *3*(4), 193-214.

Figure 1: A golfer's position and discrete time points as used in this study: address, top of the backswing and ball impact. The movement was divided into two phases: backswing (from address to the top of the backswing) and downswing (from top of the backswing to ball impact). Right handed golfers have the left side as lead and the right side as trail.

Figure 2: Mean (SD) resultant %GRF on both lead and trail during the backswing (I and III) and downswing (II and IV) for the group (n=8) immediate intervention (I and II) and the longitudinal case study (n=1) intervention (II and IV). pre ——— post ——— the intervention where solid is the lead and dashed is the trail sides. Statistical parametric maps (SPM) for the GRF data where the shaded areas show when the significant differences occur ($p < 0.05$). All curves were time normalised.

Figure 3: Mean (SD) ankle joint angles for the trail leg in the sagittal (I; dorsi/plantarflexion), frontal (II; inversion/eversion) and transverse (III; internal/external rotation) planes. pre ——— post ——— for the group and case study golfer. Positive values are dorsiflexion, inversion/adduction and internal rotation. IV, V and VI are the corresponding statistical parametric maps (SPM) for the ankle angle data where the shaded areas show when the significant differences occur ($p < 0.05$). All curves were time normalised.

Figure 4: Mean (SD) ankle joint angles for the lead leg in the sagittal (I; dorsi/plantarflexion), frontal (II; inversion/eversion) and transverse (III; internal/external rotation) planes. pre ——— post ——— for the group and case study golfer. Positive values are dorsiflexion, inversion/adduction and internal rotation. IV, V and VI are the corresponding statistical parametric maps (SPM) for the ankle angle data where the shaded areas show when the significant differences occur ($p < 0.05$). All curves were time normalised.

Figure 5: Mean (SD) knee frontal (varus / valgus) and hip transverse (internal / external rotation angles): (I) trail knee backswing; (II) trail knee downswing, (III) lead knee downswing, (IV) trial hip backswing and (V) lead hip downswing. pre——— post——— for the group and case study golfer. Positive values are varus/adduction (I, II and III) and internal rotation (IV and V). VI, VII, VIII, IX and X are the corresponding statistical parametric maps (SPM) for the ankle angle data where the shaded areas show when the significant differences occur ($p < 0.05$). All curves were time normalised.

The effect of alterations in foot centre of pressure on lower body kinematics during the 5-iron golf swing.

LESLEY FAUX[1], ALISON CARLISLE[1], JOHN VICKERS J[2] & CERI DISS[1]

[1]*Department of Life Sciences, University of Roehampton, London, UK.*

[2]*Golf Swing Body Mechanics International, Miami Beach, Florida, USA*

Correspondence: Dr Ceri Diss, Department of Life Sciences, University of Roehampton,
Holybourne Avenue, London SW15 4JD, United Kingdom.
Email: c.diss@roehampton.ac.uk

Running title: Weight distribution during the golf swing

The effect of alterations in foot centre of pressure on lower body kinematics during the 5-iron golf swing.

Abstract

The research aimed to evaluate the effects of an intervention aimed at altering pressure towards the medial aspect of the foot relating to stability mechanisms associated with the golf swing. The hypothesis that by altering the position of the foot pressure, the lower body stabilisation would improve which in turn would enhance weight distribution and underpinning lower body joint kinematics. Eight PGA golf coaches performed five golf swings, recorded using a nine-camera motion analysis system synchronised with two force platforms. Following verbal intervention they performed a further five swings. One participant returned following a one-year intervention programme and performed five additional golf swings to provide a longitudinal case study analysis. There were no changes in golf performance evidenced by the velocity and angle of the club at ball impact. although the one-year intervention significantly changed the percentage of weight experienced at each foot in the final 9% of downswing, which provided an even weight distribution at ball impact. This is a highly relevant finding as it indicates that the foot centre of pressure was central to the base of support and in-line with the centre of mass, indicating significantly increased stability when the centre of mass is near maximal acceleration.

Keywords: golf biomechanics; foot pressure distribution; injury; longitudinal intervention

Introduction

The golf swing is a whole body multi-joint movement utilised by the golfer to propel a golf ball in a pre-determined direction (Maddalozzo, 1987). There is an integral relationship through the entire movement, from the golfers' address (ADD) to top of the back swing (ToBS) and returning the club to ball impact (BI) as illustrated in Figure 1. The swing's momentum transfers through the kinetic chain from the feet, pelvis, trunk, arms and club, finally connecting with the golf ball, resulting in ball projection (McHardy & Pollard, 2005). To generate a repeatable efficient physical movement that tolerates alternating situations during competitive play a golfer requires a co-ordination of specific body components to activate in the correct sequence (Abernethy, Neal, Moran, & Parker, 1990; Neal et al., 2008). The efficiency of the golfer is dependent on maintaining a stable centre of mass (CoM). Consequently, the golfer aims to limit the medio-lateral, anterior-posterior and vertical movement of the CoM, whilst generating their maximal change in momentum during the swing to propel the ball over horizontal distances of approximately 230m (Hume, Keogh & Reid, 2005).

****Figure 1 near here****

Previous research has implicated that controlled movement of the CoM, ranges of angular motion (RoM) at the hip, knee and ankle joints, lower body internal rotation moments and efficient weight-shift patterns (i.e. movement of the centre of pressure within the base of support), all have a role in determining the golfers skill level (Gatt, Pavol, Parker, & Grabiner, 1998; Hume, Keogh, & Reid, 2005; Lephart, Smoliga, Myers, Sell, & Tsai, 2007). Farrally et al. (2003) suggested that swing consistency is compromised when there is excessive movement of CoM during the backward and downward swing. Highly skilled players display a similar kinematic sequence and have sufficient stability to control the movement of the CoM by holding a correctly aligned spine angle whilst minimising the displacement of the pelvis (Tinmark, Hellström, Halvorsen, & Thorstensson, 2010). Mayer et al. (2008) reported that increased ball velocity can be achieved by increased torso-pelvic separation whilst maintain a pelvic stability. Faster BI velocities have been associated with a stable pelvic rotation at the end of the backswing, increased trunk rotation velocity during downswing, and high acceleration of the trunk segment through to impact (Chu, Sell, & Lephart, 2010; Hume et al., 2005).

An understanding of the distribution of forces between each foot during the swing as fundamental for achieving optimal biomechanics that contribute to peak performance without incurring injury (Barrentine, Fleisig, Johnson, & Woolley, 1994). Furthermore, correct distal to proximal sequence and coordination of lower body segments provides efficient energy transfer and power at BI whilst minimising the potential for injury (Hellströn, 2009). The summation of forces principle defined as ‘the increase of velocity at the most distal segment’ (Hume et al., 2005), combined with correct and timely weight-shift transfer is integral to the swing. Lack of correct and consistent weight-shift prevents significant transfer of forces to the club-head, ultimately inhibiting the ‘squaring’ or optimal angle of the club-head to the ball at impact. Highly skilled golfers employ a fast, common weight shift compared to the erratic patterns of novice golfers (Barrentine et al., 1994). The desired maximal changes in momentum and the weight shift that occurs during the backswing to the downswing renders the body vulnerable to a myriad of injuries.

Both pronation and supination of the foot have been shown to be essential for momentum and neutral, optimal balance when standing. When sufficient pressure is on the medial portion of the calcaneus (medial tuberosity) and the distal head of the first metatarsal of the foot, the mid tarsal joint unlocks resulting in a flexible and adjustable dorsal foot surface which is key to maintaining balance (Astrom & Anlidson, 1995). When this does not occur, the foot may not adequately adapt, increasing the requirement on surrounding musculoskeletal structures to maintain postural stability, and subsequently causing compensation in other areas resulting in unnecessary, excessive movement of the lower body (Winter, 1995). Translating this key principal of balance and stability to the golf swing, Richards, Farrell, Kent, & Kraft, 1985 found a more efficient and rapid weight-shift on the lead foot after adjustments to the centre of pressure to various points on the foot leading to an increase to the base of support during downswing and hence stability. Cote, Brunet, Gansneder, & Shultz (2005) demonstrated that when the foot is slightly inverted, partial medial contact is lost with the ground, and it is not possible to subsequently control the weight-shift pattern effectively. Therefore, it is anticipated that when this foundation of foot pressure distribution is applied correctly, there will be a greater control of CoM motion due to the enhanced stability and this was the rationale for conducting the study. Using this premise an intervention to adjust medial pressure on each foot during the golf swing was developed with the aim of quantifying the effects of this intervention on lower body biomechanics. Initially the immediate effects of the pressure intervention were examined on a group of experienced golfers. Group analysis on the golf swing, which is inherently varied (Hume et al., 2005; McNitt-Gray, Munaretto, Zaferiou, Requejo, & Flashner, 2013), provides a trend from the biomechanical data sets examined (Ball & Best, 2012) whereas a case study approach bridges the science-practice gap providing application to individual golfers (Halperin, 2018). Hence, the long term outcomes of the intervention for one single case study golfer was conducted.

The intervention aimed to increase pressure medially to the forefoot and heel of the trail foot during the backswing and equally on the lead foot during the downswing. Therefore, both the immediate and longitudinal intervention examined the differences in ground reaction forces (GRF) and lower body angles and hypothesised that the intervention would induce the following changes:

1. An even weight distribution in the latter part of the downswing, evidenced by the distribution of the GRF (%GRF), increasing the body's stability with the CoP being central to the base of support at BI.
2. Alter the position of the subtalar joints and the ankle angles in all three planes.
3. Decreased trail (knee) valgus angles during both the backswing and downswing, and decreased lead (knee) valgus during the downswing which will affect knee angles in the frontal plane.
4. Minimise internal hip rotation in the trail side during the backswing and the lead side during the downswing to infer greater stabilisation of the knee (Powers, 2010).

Methods

Eight male participants (mean (±SD)): height 1.81 m (±0.05); mass 89.13 kg (±6.66)); age 45 years (±6) were recruited to the study with one of the golfers returning to the study one year later. All participants were professional golf association (PGA) qualified coaches with a zero handicap. The University's Ethics Board granted approval and written informed consent was obtained from each participant. Each of the participants used the same dedicated 5-iron club throughout the duration of the study. The club's sole purpose was to reduce variability in this research and it was not used in any other capacity. They wore their own golf shoes standing on two uncovered force plates located side by side; the researcher adjusted the tee-off position to suit their stance. Participants performed multiple practice swings for self-determined familiarisation within the laboratory environment. After familiarisation, each participant then performed between five and ten swings with maximum velocity at BI. The number of swings were self-determined by the golfers where they ensured that they had performed at least five 'good swings'. The participants aimed the ball into a net 6m from the tee-off position. The participants then received a verbal intervention and were instructed to increase foot pressure on to the medial portion of the ball and heel of the foot, increasing eversion in both backswing and downswing. Specifically, just prior to the initiation of the backswing they were asked to apply pressure vertically onto the medial part of the trail foot (putting the foot into slight pronation), then prior to initiation of the downswing the instruction was to apply pressure vertically on to the medial portion of the lead foot. The verbal information was the same for each participant and all adjusted their technique in accordance with the feedback. The feedback aimed to mimic a real-life coaching session and therefore each participant was provided with a visual demonstration of the technique coupled with verbal instruction in a language they would understand. Following this, the participants performed a further five to ten golf swings at a maximum velocity at BI. The case study golfer received 30 coaching sessions over a one-year programme, typically two or three times per month. The case study intervention sessions comprised of the visual demonstration of the technique coupled with verbal instruction on the changes on foot pressure, which were delivered by the lead researcher, whom is a golf specialist. Returning to the laboratory after one year the golfer performed five to ten swings at a maximal velocity at BI. The laboratory setup was identical one year later for the case study and the participant wore the same shoes. Five golf swings were analysed for each condition (pre and post immediate intervention, pre and post long term intervention) which were selected by the golfer's self-determined assessment of a 'good shot'.

All golf swings were recorded with a nine camera (sample rate: 100 Hz) infra-red Vicon MXF20 motion analysis system (Vicon Motion Systems Ltd, UK) synchronised with two 0.6 x 0.4m Kistler (sample rate: 1000 Hz) 9281CA force plates (Kistler Instruments Ltd, UK). Sixteen retro-reflective markers were placed on precise anatomical landmarks of the lower body according to the protocol (Davis, Ounpuu, Tyburski, & Gage, 1991). There were an additional three markers placed on the golf club (top of the shaft just below handgrip, mid-shaft and club head) and reflective tape was wrapped around the golf ball to identify the time of BI. The cameras were up-graded to a 12 camera system when the golfer returned after one year.

Data was processed using Nexus version 2 (Vicon Motion Systems Ltd, UK). A 4th order Butterworth filter, with a cut-off frequency of 6Hz was applied to the coordinate trajectories and a cut-off frequency of 30 Hz was applied to the force data. Three-dimension kinematic and kinetic measures were calculated for lower body with the Vicon Plug-in-Gait model which uses the Euler angle theorem and standard inverse dynamics. The time-point prior to movement of the golf club-head defined ADD. The time-point of ToBS was the transition between club head anti-clockwise to a clockwise motion. The time-point of BI was the frame nearest to club-ball contact determined visually; the club and ball were both visible to the camera system. Backswing and downswing phases are illustrated in Figure 1. The velocity and angle of the club head at BI were determined. The % differences in lower body angles following the intervention were reported. The trail and lead angles in all three planes for the ankle, frontal plane for the knee and transverse plane for the hip were examined. The resultant GRF was determined and reported as a % of the golfers' body weight for the trail and lead sides. Matlab version 2013a (Mathworks Inc., Massachusetts, USA) was used to time normalise the angular and GRF waveform data to 100% for the two phases of the golf swing for each trial. From the pre- and post-intervention sessions (immediate and longitudinal), means and standard deviation (SD) were calculated, from the five swings where their BI velocity was maximal. For the immediate intervention analysis group means (SD) were determined for each measure.

The Shapiro-Wilk statistical test for normal distribution revealed that all measures were normally distributed for each time point across both phases. Cohen's d was calculated and corrected for a small population size using hedges g and reported the effect size (*ES*) in the for the difference in club head velocity and angle at BI.

All waveform data were analysed using the statistical parametric mapping (SPM) technique with paired sample t-test. SPM was designed especially for continuous field analysis (Penny, Friston, Ashburner, Kiebel, & Nichols, 2011) and constructs images that lie in the original, biomechanically meaningful sampling space (Pataky, 2010). Open-source one-dimensional package for Matlab (spm1d version M.0.3.1 (2015.08.28)) was used in the analysis and the scalar test statistic SPM*{t}* was computed at each point in the time series as described previously (Robinson, Donnelly, Tsao, & Vanrenterghem, 2013).

Results

Following the immediate intervention the mean (SD) club head velocity at BI for the group changed from 31.02 m·s^{-1} (1.27) to 30.63 m·s^{-1} (1.84), (difference = -1.26 % (*ES* = 0.23) with an angle change from 7.47^{o} (1.69) to 6.62^{o} (3.22) (difference = -7.65%, *ES* = 0.22). Following the longitudinal intervention the mean (SD) club head velocity at BI changed from 31.22 m·s^{-1} (0.51) to 31.39 m·s^{-1} (0.44), (difference = 0.54 %, *ES* = 0.32) with an angle change from 7.95^{o}

(1.36) to 1.69^o (8.86) (difference -14.09%, *ES* = 0.53).

It was hypothesised that the intervention would induce an even weight distribution in the latter part of the downswing, evidenced by the %GRF distribution.

****Figure 2 near here****

Figure 2 illustrates the SPM analysis, which revealed no significant differences in any waveform data except for the lead side following the longitudinal intervention for the case study golfer ($\alpha = 0.05$, $t^* = 6.047$, $p = 0.015$) where significant differences occurred from 91% of the downswing up to BI (equating to 0.26s before impact).

****Figures 3-5 near here****

Figures 3 to 5 examine the backswing and downswing kinematic waveforms and significantly different portions in the curves are indicated by the shaded areas from the SPM analysis. Notably, significant changes in the angles examined during the backswing and downswing phases following the longitudinal intervention whereas limited significant changes in such measures following the immediate intervention.

Discussion

The biomechanical consequences following a verbal instruction to alter foot pressure during the golf swing was examined for a group of golfers with a zero handicap. To explore the individual long term mechanical effects the intervention was implement over a one year training programme for a single golfer. The altered foot pressure aimed to alter the body weight distribtion and specific lower body joint angles that are deemed to underpin injury without an effect on club head velocity and angle at BI.

Small changes in club head velocity at BI were reported for all golfers. However following a one year intervention programme for a single golfer the angle of the club at BI showed a change to a slightly flatter position (by 1^o) which would effect the range and trajectory path of the ball, although there was a slight increase in velocity (*ES* = 0.53). The underpinning biomechanics as a response to the altered foot pressure were examined particularly the effects of the longitudinal intervention, in detail.

Initially hypothesised that an even weight distribution in the latter part of the downswing evidenced by the distribution of the GRF (%GRF) would occur. Figure 2 illustrates that for the case study golfer there were changes in the weight distribution which were significant ($\alpha = 0.05$, $t^* = 6.047$, $p = 0.015$) for the lead leg in the latter part of the downswing. At BI the weight distribution between the lead and trial sides were approximately 50% compared previously to a 60-40% divide, respectively. Such changes were not detected following the immediate intervention. This was a highly relevant finding since the centre of pressure was central to the base of support and hence in-line with the CoM at BI increasing stability at a crucial time during the golf swing. Improvements in stability can minimise variability of multiple golf swings during a game. Traditionally the recommendation was that 75 to 80% of the body weight should be on the lead leg (Stover & Mallon, 1992) at and after BI with a consequence of a reduction in stability and increased variability. However, a review on knee injury literature revealed that an intervention that incorporates pelvic stability aids knee rehabilitation and injury prevention (Powers, 2010). Also, it was reported that low variation improves the accuracy and reliability in the task outcomes i.e. the club head velocity and shot accuracy of the golfer's performance (Knight, 2004).

At ADD, the trail and lead ankle angles changed in all three planes for the case study golfer while the initial study participants' experienced limited changes. In addition, alterations in the angular data sets also occurred during the backswing. Most notably as the club moved to ToBS the trail ankle was in a tri-planar neutral position evidenced by zero rotation and eversion angles along with limited dorsi-flexion. Such a position improves foot-ground interface stability during the transition from backswing to downswing, which is presently a desired position to maximise the change in angular momentum (clockwise to anti-clockwise). Stable foot-ground stability initiates correct movement at the shoulders and transferred further along the kinetic chain (Marshall & McNair, 2013). During the downswing up to BI, the significant increase in trail ankle external rotation could be considered problematic. Previously, limiting ankle movement in the transverse plane has been reported in order to prevent injury but during walking, rotations of up to 15^{o} have produced a stable foot position whilst the lower leg rotates. The external rotation on the downswing was severe (36^{o}) and a negative outcome. The aim to maintain a foot flat position, with a neutral centre of pressure, could have caused such injury inducing angular motion.

A significant increase in lead ankle dorsi-flexion towards the later stages of the backswing and the initial stages of the downswing enabled a reduction in lead knee varus positioning the knee closer to neutral by approximately 12^{o} compared to prior the intervention (Basnett et al., 2013). Therefore the lead ankle coupled with the trail improved the stability of the golfer at the crucial temporal part of the golf swing. The outcomes of the changes in the ankle joint kinematics partially supported our expected findings.

The knee joint was examined for varus/valgus angles following the theorised changes of improved knee alignment in the frontal plane. A negative consequence of the intervention was the increased valgus for the trail knee from 40% of the backswing through to BI for the case study golfer and during the final 20% of the backswing for the group (immediate intervention) golfers. For the lead knee during the downswing there was a significant reduction in the varus angle with the knee moving into minimal valgus at BI. The intervention, to some extent, in the frontal plane at BI for the lead knee has improved the desired alignment. The slight valgus position at BI does increase the adductor moments but the modern swing aims for near knee alignment at BI for the transmission of the torque and forces passing through the centre of the knee joint (Marshall & McNair, 2013).

The internal rotation of the trail hip during the backswing significantly reduced (~60%) thereby supporting our theorised changes. The improved neutral position of the trail hip was a direct result of the increased valgus at the knee enabling the shoulders to provide the greatest contribution to the torque on the downswing (Gluck, Bendo, & Spivak, 2008). Previously the lead hip was internally rotated during the downswing and the intervention caused a significant change in hip rotation where the joint was externally rotated at the ToBS by 15.3°. During the downswing the lead hip reduced the extent of external rotation however such an angular motion decreases the expected stability in this joint. Therefore, the predicted outcomes of reduction in internal hip rotation was partially accepted.

Conclusions drawn from this project could be criticised through limitations that present from a relatively small sample size of eight participants in the immediate intervention. The case study where one participant underwent specific training over a longer period was incorporated into the study to overcome this. However, research sample of indiscernible margins that separate highly skilled golfers, can also be a more effective representation and valid rationale using a small sample size, helping to increase statistical power. The authors acknowledge the limitation in equipment as the sampling frequency of the cameras was lower than ideal; furthermore, the ball tracking was not plausible within the field of view and the available technology.

Conclusion

Immediate intervention of a change in centre of pressure during the gold swing provided insight on the potential long term changes that can occur in GRF distribution and ankle, knee and hip joint angles that are associated with injury. The longitudinal one-year intervention programme caused a slight increased club head velocity (*ES* = 0.32) and a flatter angle of the club at BI (*ES* = 0.53). However, there was a significantly improved weight distribution particularly in the last 10% of the downswing up to BI, which enhanced lower body stability and supports our hypothesis. Simultaneously the neutral position of the trail ankle joint in the transverse and frontal planes also enhanced stability at BI, although the hypothesised changes in all ankle angles during the swing were not observed. Lead knee varus reduction at the top of the backswing and the first 20% of the downswing improved the alignment of the ankle, knee and hip which agrees with the hypothesised reduction in lead knee valgus. The hypothsised changes in hip rotation were partially accepted. The application of medial foot pressure caused a significant reduction in hip rotation for the trail leg at address and the final 50% of the backswing which would enhance the torque generated by the trunk on the downswing as the body segment moves from internal rotation to external rotation up to BI. The range of rotation at the lead hip was not excessive which has been reported to be important in the avoidance of labral pathology. Finally, this intervention demonstrated adjustments of foot pressure maybe more effective than the traditional pelvic adjustments in improving a golfer’s lower body stability.

References

Abernethy, B., Neal, R. J., Moran, M. J., & Parker, A. W. (1990). (1990). Expert-novice differences in muscle activity during the golf swing. Paper presented at the *Science and Golf. Proceedings of the First World Scientific Congress of Golf*, St Andrews (UK). 54-60.

Astrom, M., & Anlidson, T. M. D. (1995). Alignment and joint motion in the normal foot. *Orthop Sports Phys Ther, 22*(5), 216-222.

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

Barrentine, S., Fleisig, G., Johnson, H., & Woolley, T. (1994). Ground reaction forces and torques of professional and amateur golfers. Paper presented at the *Science and Golf II. Proceedings of the World Scientific Congress of Golf,* 33-39.

Basnett, C. R., Hanish, M. J., Wheeler, T. J., Miriovsky, D. J., Danielson, E. L., Barr, J., & Grindstaff, T. L. (2013). Ankle dorsiflexion range of motion influences dynamic balance in individuals with chronic ankle instability. *International Journal of Sports Physical Therapy, 8*(2)

Chu, Y., Sell, T. C., & Lephart, S. M. (2010). The relationship between biomechanical variables and driving performance during the golf swing. *Journal of Sports Sciences, 28*(11), 1251-1259.

Cote, K., Brunet, M., Gansneder, B., & Shultz, S. (2005). Effects of pronated and supinated foot postures on static and dynamic postural stability. *J Athl Train*, *40*(1), 41-46.

Davis, R. B., Ounpuu, S., Tyburski, D., & Gage, J. R. (1991). A gait analysis data collection and reduction technique. *Human Movement Science, 10*(5), 575-587.

Farrally, M., Cochran, A., Crews, D., Hurdzan, M., Price, R., Snow, J., & Thomas, P. (2003). Golf science research at the beginning of the twenty-first century. *Journal of Sports Sciences, 21*(9), 753-765.

Gatt, C. J.,Jr, Pavol, M. J., Parker, R. D., & Grabiner, M. D. (1998). Three-dimensional knee joint kinetics during a golf swing. influences of skill level and footwear. *The American Journal of Sports Medicine, 26*(2), 285-294.

Gluck, G. S., Bendo, J. A., & Spivak, J. M. (2008). The lumbar spine and low back pain in golf: A literature review of swing biomechanics and injury prevention. *The Spine Journal, 8*(5), 778-788.

Halperin, I. (2018). Case Studies in Exercise and Sport Sciences: A Powerful Tool to Bridge the Science-Practice Gap. *International journal of sports physiology and performance*, 1-9.

Hellström, J. (2009). Competitive elite golf. *Sports Medicine, 39*(9), 723-741.

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

Knight, C. A. (2004). Neuromotor issues in the learning and control of golf skill. *Research Quarterly for Exercise and Sport, 75*(1), 9-15.

Lephart, S. M., Smoliga, J. M., Myers, J. B., Sell, T. C., & Tsai, Y. S. (2007). An eight-week golf-specific exercise program improves physical characteristics, swing mechanics, and golf performance in recreational golfers. *Journal of Strength and Conditioning Research/National Strength & Conditioning Association, 21*(3), 860-869. doi:R-20606 [pii]

Maddalozzo, G. J. (1987). SPORTS PERFORMANCE SERIES: An anatomical and biomechanical analysis of the full golf swing. *Strength & Conditioning Journal, 9*(4), 6-9.

Marshall, R. N., & McNair, P. J. (2013). Biomechanical risk factors and mechanisms of knee injury in golfers. *Sports Biomechanics, 12*(3), 221-230.

McHardy, A., & Pollard, H. (2005). Muscle activity during the golf swing. *British Journal of Sports Medicine, 39*(11), 799-804; discussion 799-804. doi:39/11/799 [pii]

McNitt-Gray, J., Munaretto, J., Zaferiou, A., Requejo, P., & Flashner, H. (2013). Regulation of reaction forces during the golf swing. *Sports Biomechanics, 12*(2), 121-131.

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

Neal, R., Lumsden, R., Holland, M., Mason, B., Crews, D., & Lutz, R. (2008). Segment interactions: Sequencing and timing in the downswing. Paper presented at the *Science and Golf V: Proceedings of the World Scientific Congress of Golf*, 21-29.

Pataky, T. C. (2010). Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *Journal of Biomechanics, 43*(10), 1976-1982.

Penny, W. D., Friston, K. J., Ashburner, J. T., Kiebel, S. J., & Nichols, T. E. (2011). *Statistical parametric mapping: The analysis of functional brain images* Academic press.

Powers, C. M. (2010). The influence of abnormal hip mechanics on knee injury: A biomechanical perspective. *Journal of Orthopaedic & Sports Physical Therapy, 40*(2), 42-51.

Richards, J., Farrell, M., Kent, J., & Kraft, R. (1985). Weight transfer patterns during the golf swing. *Research Quarterly for Exercise and Sport, 56*(4), 361-365.

Robinson, M. A., Donnelly, C. J., Tsao, J., & Vanrenterghem, J. (2013). Impact of knee modeling approach on indicators and classification of ACL injury risk. *Medicine and Science in Sports and Exercise, 46*, 1269-1276.

Stover, C., & Mallon, W. (1992). Golf injuries: Treating the play to treat the player. *J Musculoskelet Med, ,* 55-72.

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

Winter, D. A. (1995). Human balance and posture control during standing and walking. *Gait & Posture*, *3*(4), 193-214.

Figure 1: A golfer’s position and discrete time points as used in this study: address, top of the backswing and ball impact. The movement was divided into two phases: backswing (from address to the top of the backswing) and downswing (from top of the backswing to ball impact). Right handed golfers have the left side as lead and the right side as trail.

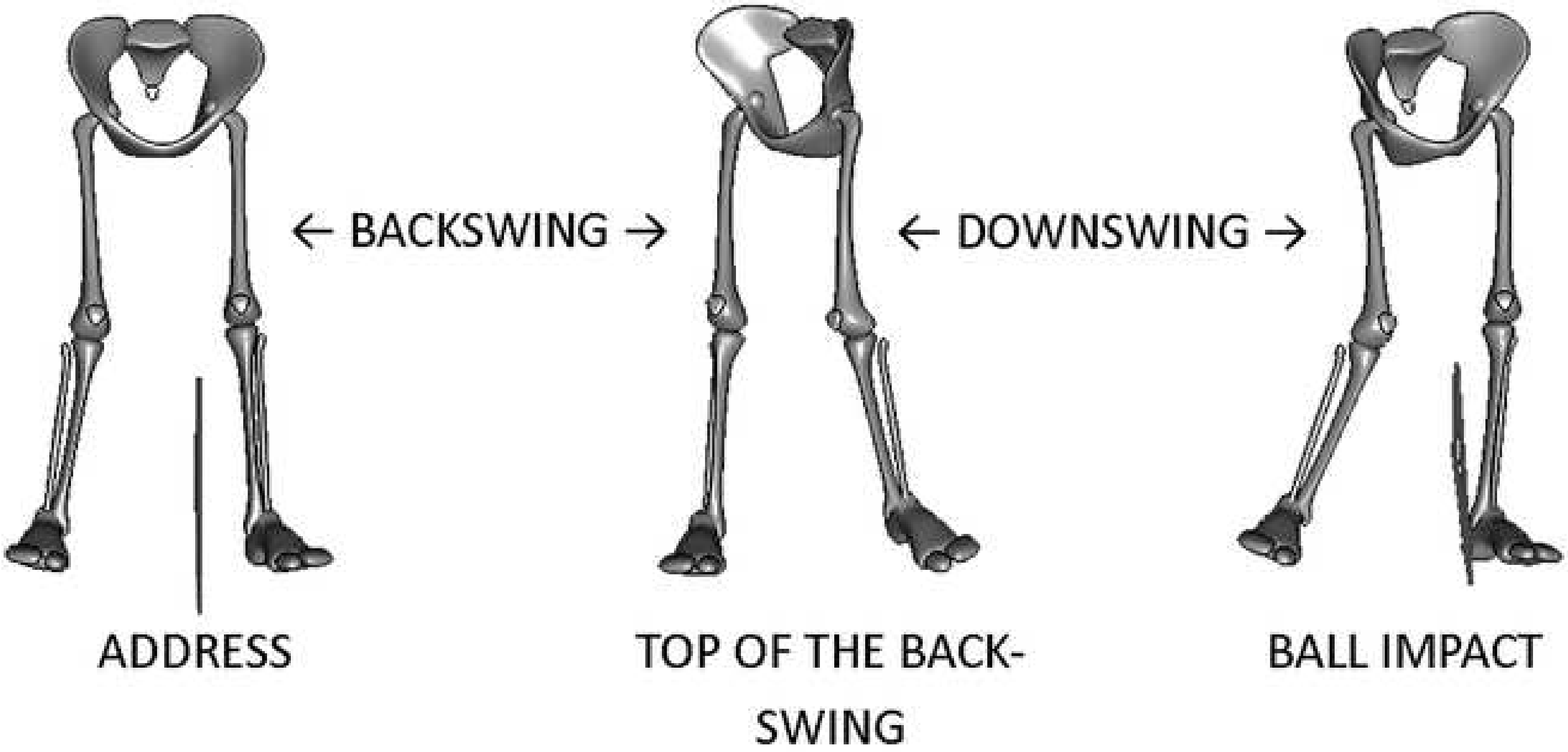
Figure 2: Mean (SD) resultant %GRF on both lead and trail during the backswing (I and III) and downswing (II and IV) for the group (n=8) immediate intervention (I and II) and the longitudinal case study (n=1) intervention (II and IV). pre ——— post ——— the intervention where solid is the lead and dashed is the trail sides. Statistical parametric maps (SPM) for the GRF data where the shaded areas show when the significant differences occur ($p < 0.05$). All curves were time normalised.

Figure 3: Mean (SD) ankle joint angles for the trail leg in the sagittal (I; dorsi/plantarflexion), frontal (II; inversion/eversion) and transverse (III; internal/external rotation) planes. pre ——— post ——— for the group and case study golfer. Positive values are dorsiflexion, inversion/adduction and internal rotation. IV, V and VI are the corresponding statistical parametric maps (SPM) for the ankle angle data where the shaded areas show when the significant differences occur ($p < 0.05$). All curves were time normalised.

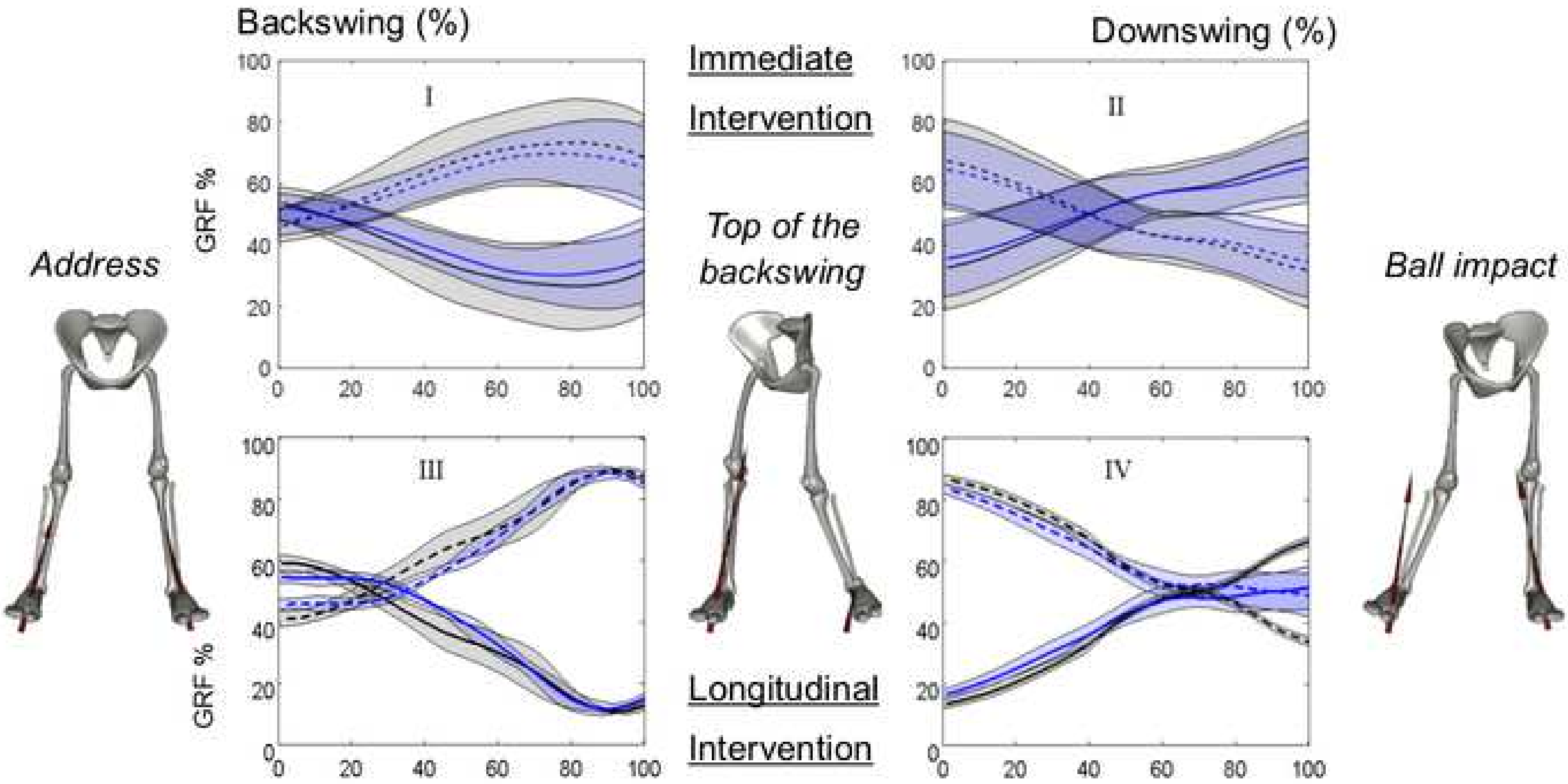
Figure 4: Mean (SD) ankle joint angles for the lead leg in the sagittal (I; dorsi/plantarflexion), frontal (II; inversion/eversion) and transverse (III; internal/external rotation) planes. pre ——— post ——— for the group and case study golfer. Positive values are dorsiflexion, inversion/adduction and internal rotation. IV, V and VI are the corresponding statistical parametric maps (SPM) for the ankle angle data where the shaded areas show when the significant differences occur ($p < 0.05$). All curves were time normalised.

Figure 5: Mean (SD) knee frontal (varus / valgus) and hip transverse (internal / external rotation angles): (I) trail knee backswing; (II) trail knee downswing, (III) lead knee downswing, (IV) trial hip backswing and (V) lead hip downswing. pre ━━ post ── for the group and case study golfer. Positive values are varus/adduction (I, II and III) and internal rotation (IV and V). VI, VII, VIII, IX and X are the corresponding statistical parametric maps (SPM) for the ankle angle data where the shaded areas show when the significant differences occur ($p < 0.05$). All curves were time normalised.

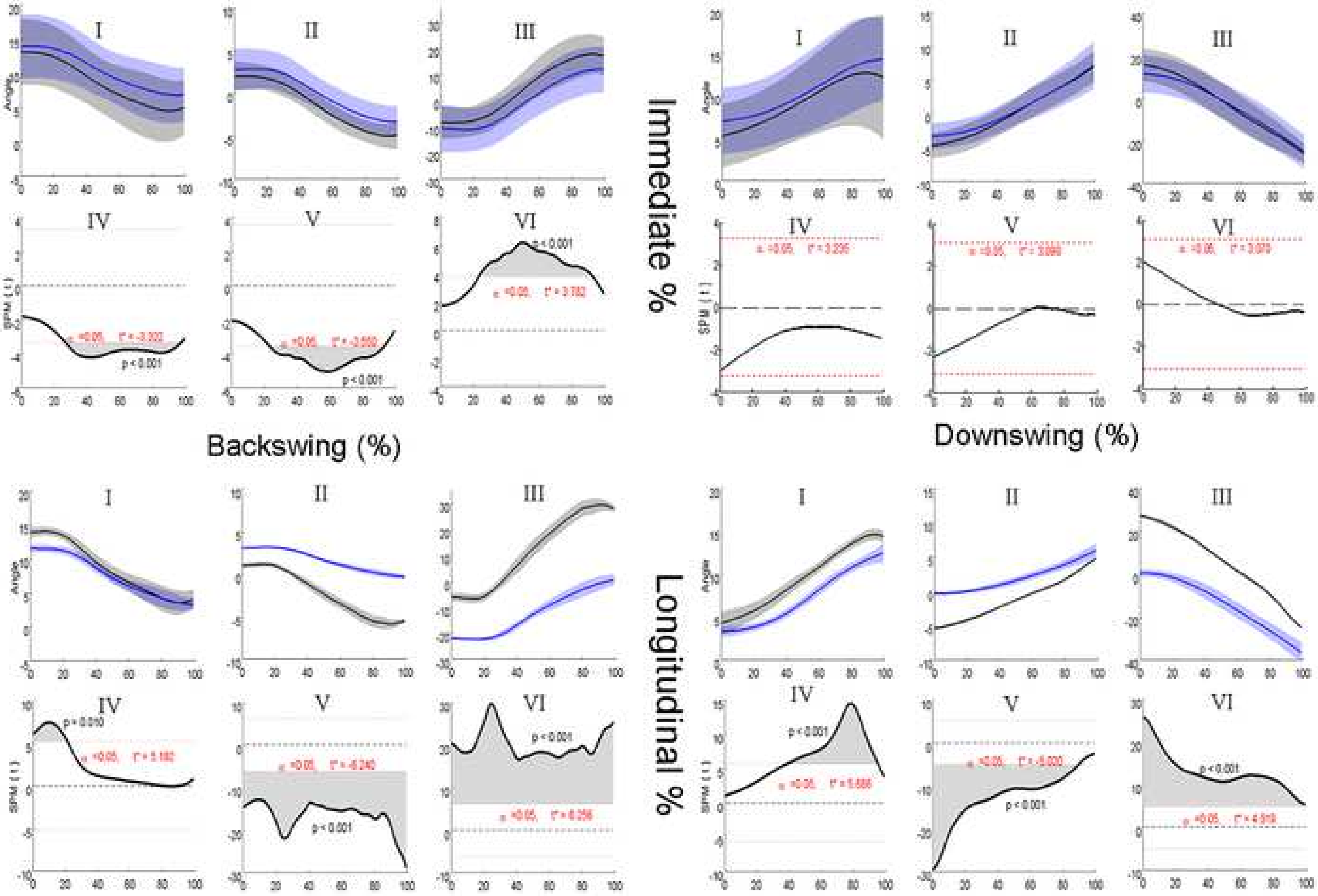
Figure


← BACKSWING →
← DOWNSWING →
ADDRESS
TOP OF THE BACK-SWING
BALL IMPACT

Figure

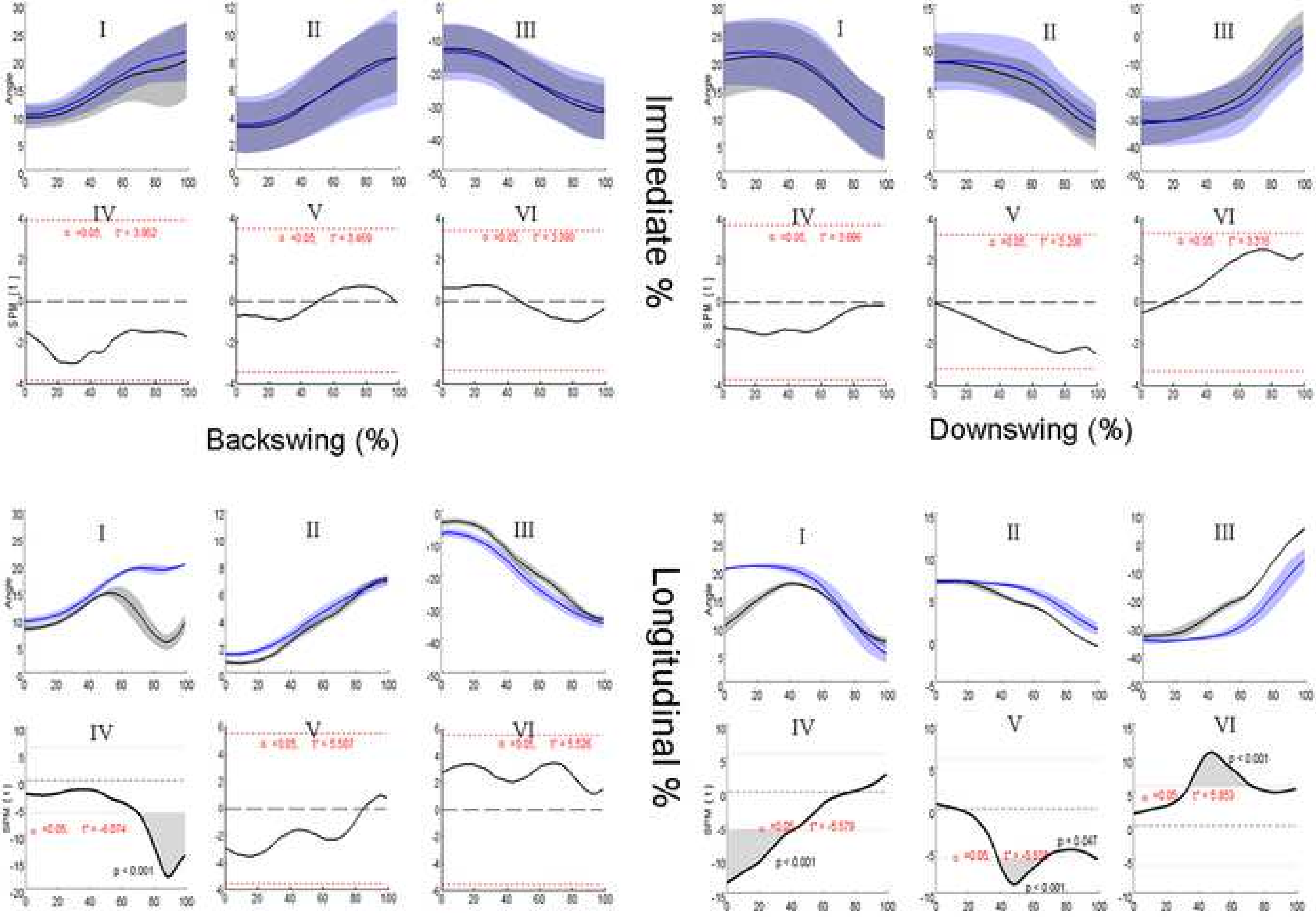

Backswing (%)
Downswing (%)
Immediate
Intervention
Top of the backswing
Address
Ball impact
Longitudinal
Intervention
GRF %
GRF %
I
II
III
IV
0
20
40
60
80
100

Figure

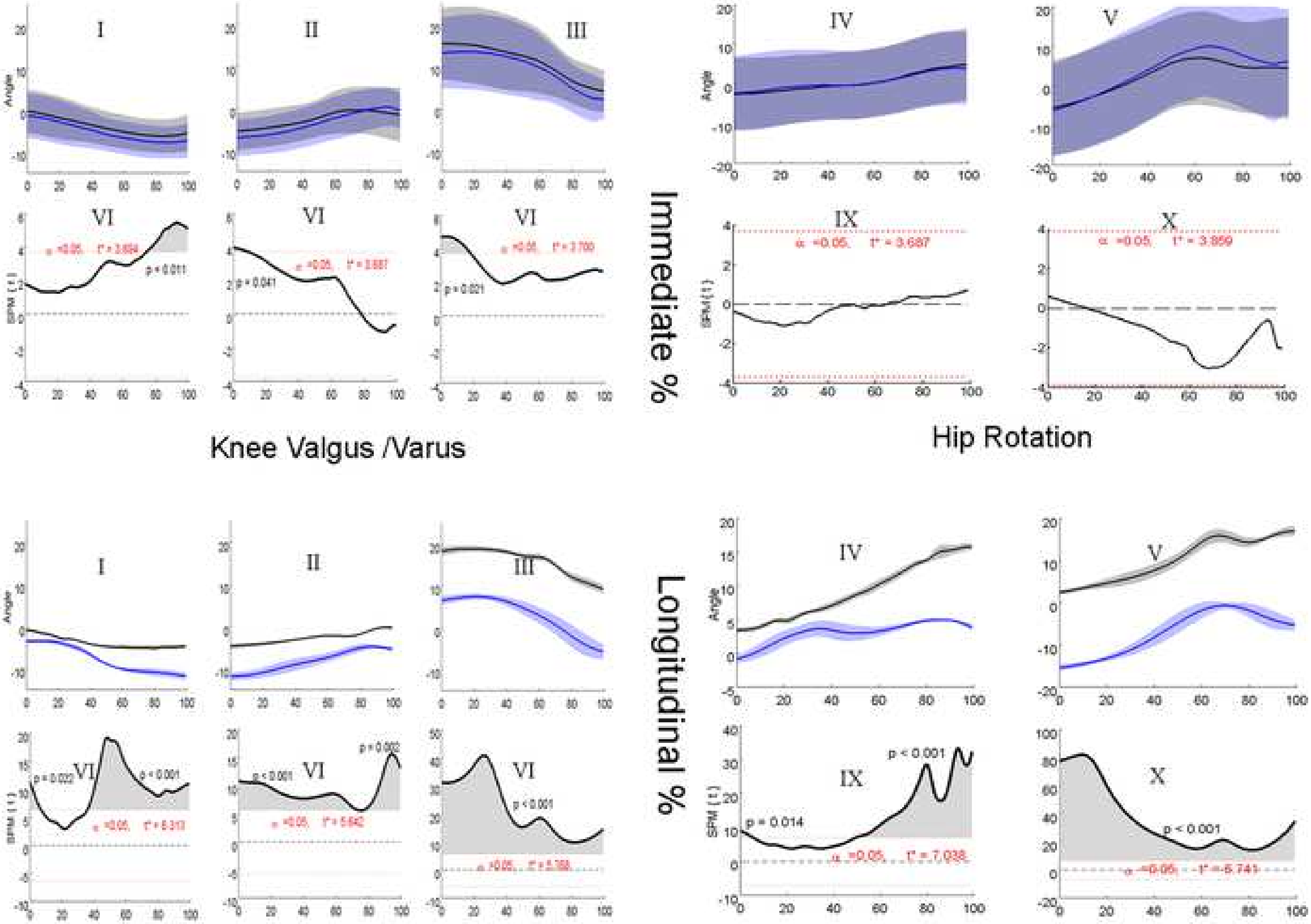


I
II
III
IV
V
VI
Angle
SPM { t }
p < 0.001
p = 0.010
Immediate %
Longitudinal %
Backswing (%)
Downswing (%)

Figure


I
II
III
IV
V
VI
Angle
SPM {t}
α =0.05, t* = 3.862
α =0.05, t* = 3.469
α =0.05, t* = 3.390
α =0.05, t* = 3.696
α =0.05, t* = 3.338
α =0.05, t* = 3.310
Immediate %
Backswing (%)
Downswing (%)
Longitudinal %
α =0.05, t* = -6.074
p < 0.001
α =0.05, t* = 5.507
α =0.05, t* = 5.536
α =0.05, t* = -5.579
p < 0.001
α =0.05, t* = -5.538
p = 0.047
p < 0.001
α =0.05, t* = 5.853
p < 0.001

Figure



I
II
III
IV
V
VI
VI
VI
IX
X
Angle
SPM {t}
α =0.05, t* = 3.694
p = 0.011
α =0.05, t* = 3.687
p = 0.041
α =0.05, t* = 3.700
p = 0.021
α =0.05, t* = 3.687
α =0.05, t* = 3.959
Immediate %
Knee Valgus /Varus
Hip Rotation
Longitudinal %
p = 0.022
p < 0.001
α =0.05, t* = 5.313
p < 0.001
p = 0.002
α =0.05, t* = 5.642
p < 0.001
α =0.05, t* = 5.368
p = 0.014
p < 0.001
α =0.05, t* = 7.038
p < 0.001
α =0.05, t* = 5.741