AUTORES:
Mário Paiva [1]
Pedro Gonçalves [2]
Filipa Sousa [1, 2]
Leandro Machado [1, 2]
João Paulo Vilas-Boas [1, 2]

[1] CIFI²D, Faculdade de Desporto Universidade do Porto, Portugal

[2] Laboratório de Biomecânica do Porto, Universidade do Porto, Portugal

https://doi.org/10.5628/rpcd.11.01.44

3D kinematic and kinetic analyses of the Golf swing using three different clubs: A case study.

PALAVRAS CHAVE:
Biomechanics. Weight transfer. Driver. Five-iron. Pitching-wedge.

ABSTRACT

The purpose of this paper was to study the kinematic and kinetic patterns of the golf swing when performed with different clubs: driver, five-iron and pitching-wedge, which provide different ball flies concerning distance, trajectory and accuracy. An amateur golf player (*handicap* EGA: 19.9; height: 172 cm; body mass: 70 kg; age: 60 years) performed six attempts with each club, with 2 min of rest between shots to prevent fatigue. Ground reaction forces were obtained by alternately placing each foot on a force platform while the subject hit golf balls on artificial turf in an indoor golf station. Three force trials for each foot were recorded and subsequently averaged using the three clubs. Simultaneous video records by three 50 Hz digital video cameras allowed kinematical evaluation using *Ariel Performance Analysis System* (*Ariel Dynamics Inc.*). Statistically significant differences were found among clubs considering club head velocity and ground reaction forces, particularly in what concerns weight transfer (WT). The driver allowed to reach the higher club head velocities (growing with the length of the club), and was characterised by a “Front Foot’’ style of WT, in opposition to the other clubs that were characterised by a “Reverse’’ style.

Correspondência: Mário Paiva. CIFI²D, Faculdade de Desporto da Universidade do Porto.
Rua Dr. Plácido Costa, 91. 4200-450 Porto, Portugal (mario.paiva@fade.up.pt).

Análise cinética e cinemática tridimensional do *swing* utilizando três tacos diferentes. Um estudo de caso.

RESUMO

O objectivo deste estudo foi investigar a influência do padrão cinemático e da transferência de peso (TP) no *swing* de três tacos diferentes: o drive (D), o ferro cinco (F5) e o *pitching wedge* (PW), que proporcionam distintos padrões de voo de bola, no que se refere a trajectória e distância. Um jogador amador (*handicap* EGA: 19.9; altura: 1.72 cm; idade: 60 anos) efectuou 6 repetições com cada um dos tacos, com intervalo superior a 2 min de forma a obstar aos efeitos da fadiga. As forças de reacção do solo durante o *swing* foram medidas utilizando uma plataforma de forças que operou a uma frequência de 1000 Hz. O sujeito colocou cada pé alternadamente na plataforma de forças. A componente vertical da força de reacção no solo foi utilizada para analisar o padrão de transferência de peso do golfista. O registo simultâneo em vídeo com câmaras de 50 Hz e a utilização do *Ariel Performance Analysis System* (*Ariel Dynamics Inc.*) permitiu identificar cada uma das fases do *swing* e a velocidade da cabeça do taco no decurso do movimento, tendo sido especialmente considerados os valores no impacto. Os resultados obtidos evidenciaram velocidades superiores da cabeça do taco para o D. O F5 também proporcionou velocidades superiores ao PW. As diferenças entre os perfis de TP sobressaíram entre o D e os restantes dois tacos, revelando-se apenas no primeiro taco uma efectiva TP para o pé da frente no impacto. Estes resultados confirmam a presença de dois estilos de transferência de peso, o *front foot* para o *driver* (67.3% da força vertical total – direita + esquerda - exercida no solo pelo membro inferior da frente na fase que inclui o contacto com a bola) e o *reverse style* para o *pitching wedge* e ferro 5 (respectivamente, 77.4% e 77% da força total exercida no pé de trás, na fase que inclui o contacto com a bola).

KEY WORDS:

Golfe. *Swing*. Transferência de peso. Cinemática. *Driver*. Ferro 5. pitching-wedge.

INTRODUCTION

In the published literature, only few articles can be found concerning the biomechanical analysis of the swing performance of the same player, or of a given sample of players, using different clubs. From them, Barrentine et al. [5], Koenig [18], Koslow [19], and Williams and Cavanagh [32], showed that the weight shifting process between the feet is influenced by the club used. Weight transfer (WT), or weight shift, is a coaching expression used to describe the motion of the centre of pressure, or the distribution between the feet of the 3 components of the ground reaction force during the golf swing. Several authors found statistically significant differences between different skill level golfers (from professional to high handicap) when analysing the WT between swings [5, 12, 18, 27]. Besides, Gatt et al. [12], Koenig et al. [18], Wallace et al. [31] and Williams and Cavanagh [32], while studying the WT, found significant differences between golfers when using different shoes (metal spikes or soft spikes). Another study of Ball et al. [2] focused on the analysis of shot to shot differences in the golf swing WT concerning short or long term variability between golfers. Egret et al. [9, 10] found that elite players swung the pitching wedge, the five-iron, and the driver with identical timing for each swing phase among the three clubs, but kinematics and club-head speeds differed. Kaneko and Sato [16] reported that different types of clubs may change the golf swing, while Budney and Bellow [6] found out that the inclination of the swing plane was different for each club, and also that the length of the backswing increased with the club length. Nagao and Sawada [22] observed that the non dominant arm speed was higher for the driver, and decreased for each club according to its length.

Proper and timely WT during the swing is a determinant part of successful golf [15]. It is usually referred that a critical point for the swing technique is to have, at set-up, body weight equally distributed over the base of support, subsequently transferred to the back foot at the top of the backswing, followed by a shift towards the front foot at impact [8, 19, 32]. Burden et al. [7], studying patterns of the centre of mass (CM) motion in sub-10 handicap players during the driving, found that the speed of the swing was influenced by the CM shifting exclusively in the intended direction of the flight of the ball during club impact. Lack of proper and consistent WT of golfers unable significant transfer of forces to the club head, and prevent the squaring of the club head at impact.

Nevertheless, Ball and Best [3, 4] grouped the several WT styles described in the literature [17, 18, 19, 20, 23, 25, 28, 30], in two classes: a ''Front Foot'' style and a ''Reverse'' style, often called as a "Reverse Pivot". In both styles, the centre of pressure was positioned near the midpoint at address, near the back foot at mid, late, and top of backswing, before moving towards the front foot at early downswing. The ''Front Foot'' style continued to move the centre of pressure towards the front foot, with the centre of pressure being positioned close to the front foot at ball contact and mid-follow-through. In contrast, for the ''Reverse'' WT pattern, the centre of pressure moved towards the back foot again and was positioned at the midpoint of the feet at ball contact, and closer to the back foot at mid-followthrough. As both WT styles were used from super skilled to high handicap golfers, and no differences were observed between handicap, distance or club head velocity at ball contact, Ball et al. [2] and Ball and Best [3] concluded that neither style was a technical error.

In any case, to maximise the distance attained with the driver, woods and long irons, the golfer needs to produce large ground reaction forces (GRF): the legs should be pushed down on the ground to increase the GRF and to enhance the transfer of bodyweight [11, 12].

Also critical to success on the golf course is a swing that can be repeated "consistently" [1], the word probably most frequently associated with successful play. To evaluate consistency of the weight transfer action, GRF components recorded in three dimensions (vertical, medial-lateral and anterior-posterior) needs to be compared at three temporal events (address, top of backswing and impact) using the different clubs.

Several studies report that novice golfers show different kinematical or kinetic characteristics when compared with the elite golfers but, to the best of our knowledge, this evidence was never provided simultaneously, with studies reporting both kinematical and kinetical data. The purpose of this paper was to study the kinematic and kinetic patterns of the golf swing of a unskilled golfer when performed with different clubs: driver, five-iron and pitching-wedge.

METHODS

DATA COLLECTION

An amateur golf player (*handicap* EGA: 19.9; height: 172 cm; body mass: 70 kg; age: 60 years), with an average of 14 hours of training per week and with a golfing experience of 5 years, volunteered for this study. The player was wearing golf shorts and soft spike shoes. He completed six attempts with each one of the three different clubs: driver, five-iron and pitching-wedge, taking 2 min of rest between each shot to avoid fatigue. The golfer provided informed consent, and signed a pre-test questionnaire, passed by the Ethics Committee of the hosting university.

The testing was performed in an indoor golf station with the subject hitting golf balls on artificial turf surface into a nylon vertical net (6x5 m^2) located 8 m apart from the golfer.

The 3D Kinematic biomechanical models of each performance were obtained using the video processing system *Ariel Performance Analysis System* (*Ariel Dynamics Inc.*) with images taken by three non co-planar digital video cameras SONY DCR HC42E (Japan), operating at 50 Hz. The DLT algorithm was used to transform planar into spatial coordinates. Kinematical data was low-pass filtered with a cut-off frequency of 10 Hz. The data at address, top of backswing, and impact were considered as critical instants of the movement [2, 3, 4, 7, 9, 10, 18, 19, 26, 27, 32].

Anatomical landmarks for the definition of body segments and creation of the biomechanical model were placed at: vertex, left and right gonium, left and right shoulder rotation centre, left and right elbow rotation centre, left and right wrist rotation centre, left and right hand third finger extremity, left and right hip rotation centre, left and right knee mean rotation centre, left and right lateral malleolus, left and right heel, and left and right first metatarsal distal extremity. The club shaft on the zenith and lower extremity of the handle and the bottom on each face of the clubhead were also used as landmarks.

To describe the 3D kinematic data of the golf swing obtained with the three different clubs, the following variables were chosen: (1) hip joint rotation angle; (2) shoulder joint rotation angle; (3) back knee joint flexion angle; (4) the stance (distance between the two feet), as well as (5) the club head speed before impact and (6) the timings of the two phases (backswing and downswing) during the swing. The zero reference of the hip and shoulder joint rotation angles was found when the biacromial and bitrochanterian lines were in the frontal plane at the beginning of the golf swing. The zero reference of the knee joint angles was obtained when the lower limbs were in complete extension. The swing was divided into two phases: (1) backswing, from address to top of backswing, and (2) downswing, from top of backswing to impact. The beginning of the movement (0%) corresponded to the first frame of the address, while the end (100%) was considered to be the frame of impact.

Ground reaction forces were obtained by alternately placing each foot on a BERTEC 4060-15 force platform operating at a sampling frequency of 1000 Hz. Amplified data were converted from analogical to digital through a Biopac A/ D converter (16 bits).

The force plate was synchronized with the three-dimensional motion analysis system through a LED placed at each camera activated simultaneously to a trigger signal from the *Acknowledge* software, such that specific points in the ground reaction force data were able to be identified in correspondence to the kinematic data and define the different phases of the swing. These phases were defined considering the time gaps between the successive critical moments commonly described in the analysis of the swing (address, takeaway, backswing mid-backswing, late-backswing, top of the backswing, early-downswing, mid-downswing, late-downswing, impact, mid- follow-through, late-follow-through and finish) [3, 4]. Force plate data were filtered through a 4th order Butterworth low-pass filter, with cut-off frequency of 50 Hz, and relevant force data at each phase (Figures 5 to 7) were obtained by a Matlab (The MathWorks, USA) routine. Data on three phases of the swing were specifically sought immediately prior to the moments considered in the literature as especially critical in executing the swing: address, top of the backswing and impact [2, 3, 4, 7, 9, 10, 18, 19, 26, 27, 32]. The choice of these phases for analysis was due to the relative inaccuracy of the determination of critical moments in time resulting from the video image's reduced frequency of acquisition.

DATA ANALYSIS

Nonparametric statistics was used given the reduced sample. Kinematic data were analysed using the Friedman test to determine significant differences between the three clubs. When the first test was significant a Wilcoxon test was used between clubs pairs (driver vs. five iron; driver vs. pitching wedge; five iron vs. pitching wedge) to determine where the differences occurred. The level of significance was set at alpha = 0.05.

Concerning kinetic data, the force curves were constructed with average values of only three repetitions for each foot for a total of 6 trials. The study of differences between the clubs in each phase was conducted through the study of the differences of the total values obtained during the backswing and during the downswing for each one of the three clubs (n=12). The level of significance was set at alpha = 0.1. The SPSS 19.0 package was used.

RESULTS

There were no significant statistical differences between the timing of each phase of the swing performed with the three clubs (Table 1). The shoulder and hip rotation angles (Figures 1 and 2) and the knee joint flexion angle (Table 2) obtained with the three different clubs at the address, top of backswing and impact were also not significantly different.

TABLE 1. Percent time duration (%) of the golf swing phases performed with a pitching wedge (Pw), a five-iron (Fi) and a driver (D). Differences were not statistically significant between clubs.

	PW	FI	D
BACKSWING	72.61 ± 3.6%	74.47 ± 2.13%	73.55 ± 1.7%
DOWNSWING	27.39 ± 3.6%	25.53 ± 2.13%	26.45 ± 1.7%

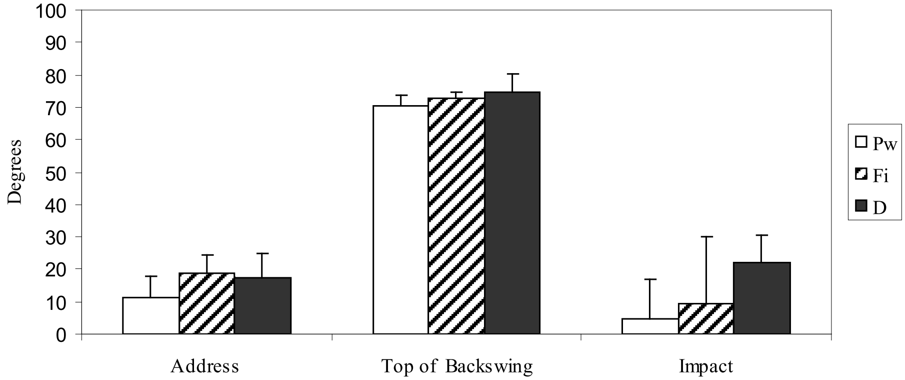


FIGURE 1 — Shoulder joint mean rotation angles (º) at address, top of the backswing, and impact when the swing is performed with a pitching wedge (Pw), a five-iron (Fi) and a driver (D). Differences were not statistically significant between clubs.

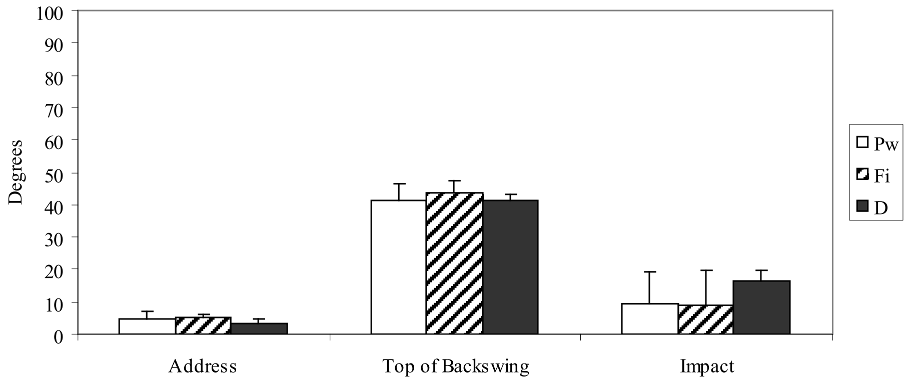


FIGURE 2 — Hip joint mean rotation angles (º) at address, top of the backswing, and impact during the swing performed with a pitching wedge (PW), a five-iron (F5) and a driver (D). Differences were not statistically significant between clubs.

TABLE 2 — Back and front knee joint flexion angles (º) at address, top of the backswing and impact during the swing action performed with a pitching wedge, a five-iron and a driver. Differences were not significant between clubs.

	BACK KNEE	FRONT KNEE				
	Address (º)	Top backswing (º)	Impact (º)	Address (º)	Top backswing (º)	Impact (º)
DRIVER	25.7 ± 4.3	12.2 ± 8.6	25.7 ± 6.0	30.9 ± 2.0	26.6 ± 7.2	29.6 ± 3.9
FIVE-IRON	25.6 ± 7.1	24.1 ± 10.0	20.9 ± 8.1	29.4 ± 2.9	21.6 ± 7.4	25.7 ± 3.6
PITCHING WEDGE	26.4 ± 6.0	23.7 ± 12.7	16.0 ± 5.3	27.5 ± 4.1	27.2 ± 5.9	28.2 ± 2.6

The subject rotate his shoulders at the top of the backswing 74.7º ± 5.7º in the case of the driver shot, 72.8º ± 1.9º with the five-iron and 70.6º ± 3.3º with the pitching-wedge.

The mean stance at address was 56.6 ± 0.03 cm with the driver, 51.4 ± 0.01 cm with the five-iron and 55.6 ± 0.02 cm with the pitching wedge. This variable showed significant difference between the clubs at address, top of backswing and impact (Figure 3), with the Five-iron being different (lower) compared with the other two studied clubs.

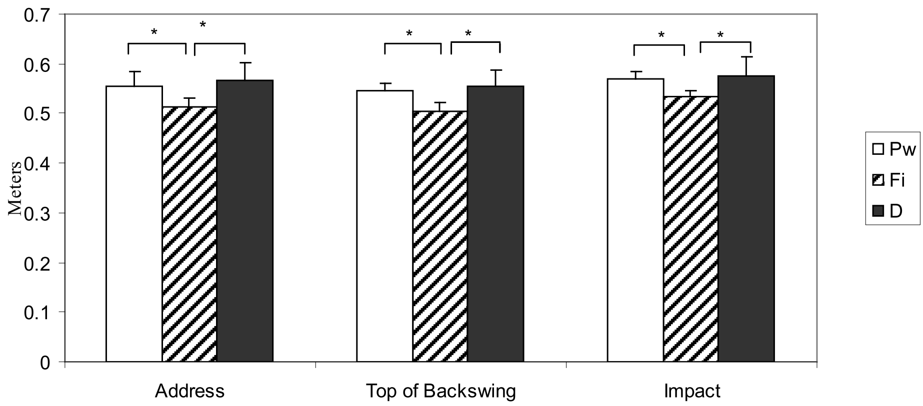


FIGURE 3 — Mean stance (m) at address, top of the backswing and impact using a pitching wedge (PW), a five-iron (F5) and a driver (D) clubs. * Statistically significant differences (p<0.05).

Regarding the club head speed, results showed significant differences between the clubs at impact (Figure 4). The driver speed at impact was 1.13 times higher than the five-iron speed (111.7 ± 7.1 km.h^{-1} vs. 98.3 ± 5.7 km.h^{-1}), and the five-iron speed was 1.07 times higher than the pitching wedge speed (98.3 ± 5.7 km.h^{-1} vs. 91.6 ± 3.6 km.h^{-1}).

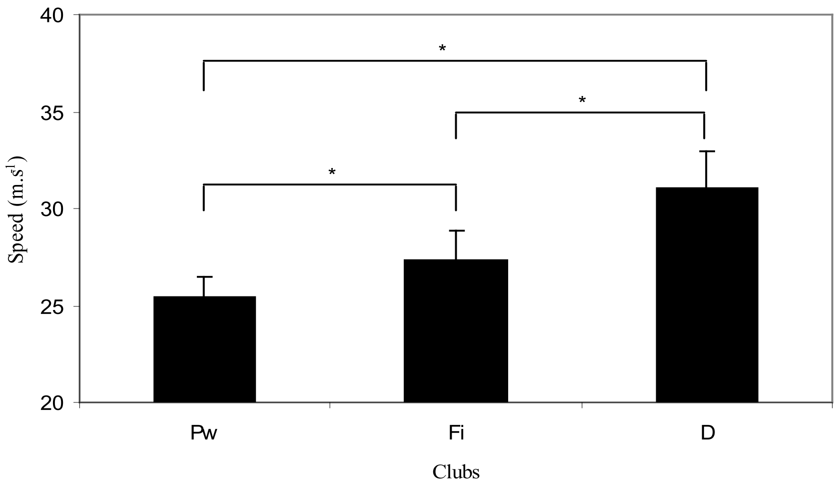
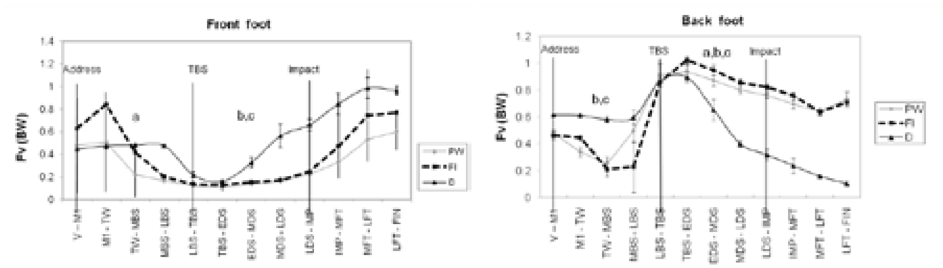


FIGURE 4 — Club head velocity (m.s^{-1}) at impact using a pitching wedge (PW), a five-iron (F5) and a driver (D) clubs. * Statistically significant differences (p<0.05).

Examining WT, during the backswing, the vertical GRF exerted on the front foot was higher for the Fi comparatively the PW, and the D did not differ from the others (Figure 5). However, during the downswing, the vertical force exerted on the front foot was higher for the D in relation to the remaining clubs studied - PW and Fi (Figure 5). We also observed that, when D is used, the rear foot support a higher vertical force than the other clubs during the backswing, but its ratio is reversed during the downswing. In fact, if we consider only the phase that includes the impact, the rear foot supports a high percentage of the total vertical GRF (front + rear feet) for the PW and Fi (77.4% and 77% respectively), while, when using the D, more than 50% of the total vertical component is exerted on the front foot (67.3%).

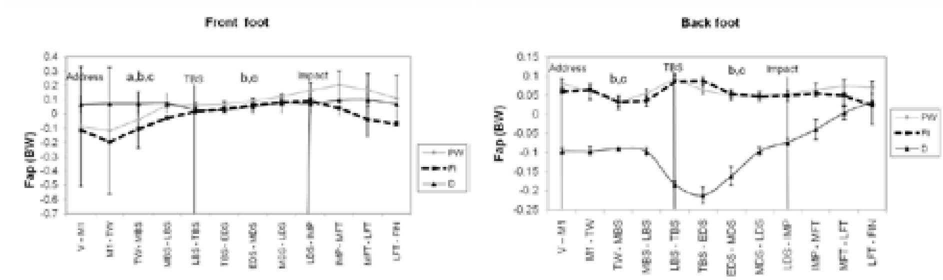
Analyzing the anterior-posterior component of GRF (Figure 6), it was observed that the D shows systematically negative values on the back foot, in opposition to the other clubs studied. The results obtained only for the phase that includes the impact (LDS-IMP) showed that the front foot supports a high percentage of the anterior-posterior component of GRF when the PW and the Fi are used (75.1% and 77% respectively), while the D is characterized by a balanced force supported by the two feet.

Regarding the GRF medial-lateral component, unlike the observed for the backswing, there were no significant differences between the three clubs taking into account the total values obtained for the front foot during the downswing. Nevertheless, there were no statistically significant differences between the D and the other clubs on the back foot in both phases (Figure 7), and the forces are exerted in the opposite direction when using the D when compared to the PW and the Fi. However, at the impact, the D supports the higher values of the medial-lateral component of the GRF among the clubs tested (67% PW, 65.1% Fi and 77.2% D).



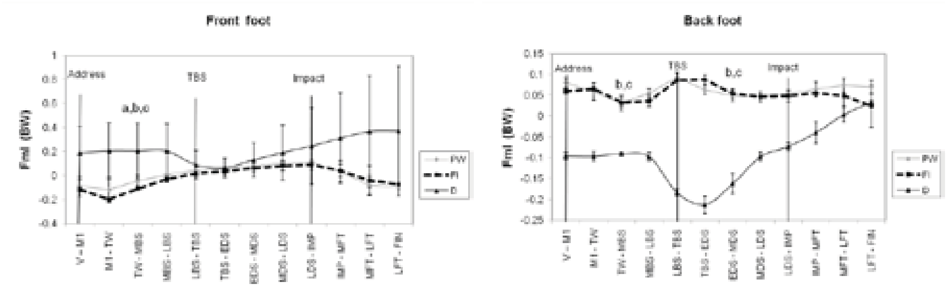
LEGEND: a = statistically significant difference between PW and Fi; b = statistically significant difference between PW and D; c = statistically significant difference between Fi and D; Fv (BW) - Vertical force (body weight) ; V - Voice; M1 - First backward movement of the club at Address; TW - 8 o'clock takeaway; MBS - Mid-backswing, club shaft parallel to the horizontal plane; LBS - Late backswing, club shaft perpendicular to the horizontal plane when club is projected onto the YZ vertical plane; TBS - Top backswing, instant before shaft begins downswing; EDS - Early downswing, club shaft perpendicular to the horizontal plane when club is projected onto the YZ vertical plane; MDS - Mid-downswing, club shaft parallel to the horizontal plane; IMP - Impact, instant of club contact with ball; MFT - Mid-follow-through, club shaft parallel to the horizontal plane; LFT – Late follow-through, club shaft perpendicular to the horizontal plane when club is projected onto the YZ vertical plane; FIN – Finish.

FIGURE 5 — Vertical component of the ground reaction force (fraction of body weight) at address, top of the backswing and impact recorded with a pitching wedge (Pw), a five-iron (Fi) and a driver (D) clubs concerning front (left) and back (right) feet.



LEGEND: according to Figure 5.

FIGURE 6 — Anterior/ posterior component of the ground reaction force (fraction of body weight) at address, top of the backswing and impact recorded with a pitching wedge (Pw), a five-iron (Fi) and a driver (D) concerning front (left) and back (right) feet. Legend: according to Figure 5.



LEGEND: according to Figure 5.

FIGURE 7 — Medial/ lateral components of the ground reaction force (fraction of body weight) at address, top of the backswing and impact recorded with a pitching wedge (Pw), a five-iron (Fi) and a driver (D) concerning front (left) and back (right) feet.

DISCUSSION

The main purpose of this study was to investigate the influence over the golf swing kinetic pattern of the use of three different clubs, particularly trying to find out if any biomechanical changes in the swing technique are attributable to the club used. Most of our results showed relevant statistical differences in WT between lower limbs for the different clubs.

Results indicate that the unskilled golfer that was analysed has a tendency to place his weight on the back foot at the moment of contact with the ball, when using the pitching-wedge and the five-iron ("Reverse'' style), and on the front foot when using the driver ("Front Foot'' style). This finding confirms that the reverse style for WT is present in a majority of mid- to high-handicap golfers (17). Koslow (19) reported that 84% of novice golfers did not exhibit the normal pattern ("Front Foot"), producing, instead, a "reverse pivot" or an incomplete WT that will result in an open club face during ball contact, causing the ball to fade or slice. Richards et al. (27) suggested that, in order to effectively use the GRF, the timing and the magnitude of the WT is more important than simply the magnitude of the GRF. In fact, our golfer WT does not occur in optimal time, since the higher values of the vertical component of the GRF occurs between the late-follow-through and finish, while they should occur only a few milliseconds before impact (see Figure 5). Theoretically, the maximum values of the vertical GRF component, and club head velocity should occur simultaneously at impact, or very close to it, allowing the achievement of greater ball distance. When hitting a driver, vertical, anterior-posterior and medial-lateral peak GRF of 1.6 to 2.0 BW, 0.4 to 0.6 BW and 0.2 to 0.3 BW, respectively, have been observed (5, 11, 18). Okuda et al. (26) reported that the vertical ground reaction force of a professional golfer increased to 1.84 BW at the impact, which is 2.9 times greater than at address. Reversely, in our study, the vertical ground reaction force at impact of the tested unskilled golfer is similar to that at address (Figure 5).

The golf swing is organized according to the principle of sequential summation of (segmental) forces [7, 14, 21]. The kinetic chain begins in the lower limb and follows through the pelvis, trunk, shoulder, elbow and hand, transferring to the club all the energy gained. An incorrect WT in this proximal-to-distal pattern of movement causes numerous errors in the swing [15]. Accordingly, the biomechanical analysis of the golf swing is able to allow the identification of specific biomechanical performance parameters that discriminate different levels of performance of the performer.

The second purpose of this paper was to study the influence of the use of three different clubs over the golf swing kinematic pattern. Results pointed out only few kinematical effects, specifically focused on the club head velocity.

Concerning the shoulder joint rotation angles measured at the top of the backswing with reference to the frontal plane, statistical analysis didn't show differences between the driver, the five-iron and the pitching wedge. Besides, shoulder joint rotation angle data for the pitching-wedge and the five-iron at the top of backswing are larger than for the driver, which may be due to the use of the "Reverse foot" style with the irons, in opposition to the driver "Front foot" style, which probably boost an over swing. Our results (71º-75º) aren't similar to other studies where the mean shoulder joint rotation angles varies from 78º to 102°, depending on the level of expertise [1, 7, 10], while for professional golfers could it fall between 90º and 130º [7, 10].

Regarding the average hip rotation at the top of the backswing, the statistical analysis didn't show differences between the three clubs, and our results (41º–45°) were coherent but lower than those observed in other studies (47º–55°) [1, 7, 10].

The knee flexion angle should also be considered when evaluating shoulder and hip rotation angles, as the inclination of the swing plane can be affected. During the address, the knees should be flexed to 20º–25° [13]. For a right-handedness golfer, the right pelvic rotation causes internal rotation of the right femur throughout the backswing. If this action is inadequately performed (i.e. <30°), the anterior superior iliac spines will tilt from the desired horizontal position, the back knee flexion angle will extend from the desired 20° knee flexion, and the primary and secondary spine angles will be changed [14]. Our results were higher than the previously reported by other studies [9, 10, 11, 12], reinforcing that biomechanical parameters can discriminate low level from expert players. Furthermore, statistical analyses didn't revealed significant differences between the driver and the other clubs for the back knee flexion at the top of the backswing, showing an improper value for the driver (D-12.2 ± 8.6º; Fi-24.1 ± 10º; Pw-23.7 ± 12.7). Budney and Bellow [6] and Egret et al. [10] reported that the inclination of the swing plane is different for each club, more vertical for the driver than for the five-iron or the pitching wedge, when considering knee angles, stance and shoulder angles together.

The stance at address (Figure 3) didn't increase with the length of the club, which disagrees with previous studies [10, 22], probably due to the expertise level of the studied player that didn't regularly adapt the stance to each particular exercise condition. Nevertheless, the statistical analysis showed several differences between the three clubs: the mean stance at address was 56.6 cm in the case of the driver shot, 51.4 cm in the case of the five iron and 55.6 cm for the pitching wedge.

Concerning club head velocity, our results (Figure 4) showed that it increased with the length of the club (Pw-25.4 $m.s^{-1}$; Fi-27.3 $m.s^{-1}$; D-31 $m.s^{-1}$) and there were found significant velocity differences between the clubs, both in agreement with previous studies [6, 10, 22, 24].

Analysing each separate phase of the swing (backswing and downswing), the movement duration for each club didn't show significant differences, which is in agreement with the results of other studies [10, 22], with the exception for Budney and Bellow [6], who referred that the duration of the backswing increased with the club length.

CONCLUSION

The results of this study allow concluding that the unskilled golfer swing differ kinematicaly and kinetically between the driver, the five-iron and the pitching-wedge, reinforcing the opinion of several researchers that the type of club used could significantly alter the swing

The results of this study let also conclude that this amateurish golfer using the short and medium irons of our study (pitching wedge and five iron) exhibited weight shifts which did not conform to the commonly prescribed weight transfer pattern style in which weight moves from a centred position at address to a position in which weight is predominantly on the rear foot at the top of the backswing and then is transferred to the front foot at impact. On the opposite, using the driver, he exhibited a conventional weight shift. In synthesis, it become clear from the results of the present study that weight transfer may be different for different clubs used for the same player.

REFERENCES

1. Adlington GS (1996). Proper swing technique and biomechanics of golf. *Clinics in Sports Medicine, 15*: 9-25.

2. Ball K., Best R, Dowlan S (2007). Non linear analysis of centre of pressure patterns in the golf swing – Poincare plots. *Proceedings of the XXV ISBS Symposium 2007*. Ouro Preto – Brazil., 180-183.

3. Ball KA, Best RJ (2007). Different centre of pressure patterns within the golf stroke I: Cluster analysis. *Journal of Sports Sciences, 25*(7): 757-770.

4. Ball KA, Best RJ (2007). Different centre of pressure patterns within the golf stroke II: group-based analysis. *Journal of Sports Sciences, 25*(7): 771-779.

5. Barrentine SW, Fleisig GS, Johnson H et al. (1994). Ground reaction forces and torques of professional and amateur golfers. In: Farrally MR, Cochran AJ (Eds.), *Science and golf II. Proceedings of the 1994 World Scientific Congress of Golf*. London: E & FN Spon, 33-39.

6. Budney DR, Bellow DG (1982). On the swing mechanics of a matched set of golf clubs. *Research Quarterly for Exercise and Sport, 53*(3): 185-192.

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

8. Cooper JR, Bates BT, Rede J, Scheuchenzuber J (1974). Kinematic and kinetic analysis of the golf swing. In: Nelson RC, Morebouse CA (Eds.), *Biomechanics IV*. Baltimore, MD: University Park Press, 298-305.

9. Egret CI, Nicolle B, Dujardin FH, Weber J, Chollet D (2006). Kinematic analysis of the golf swing in men and women experienced golfers. *International Journal of Sports Medicine, 27*(6): 463-467

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

11. Gatt CJ Jr, Pavol MJ, Parker RD, Grabiner MD (1998). Three dimensional knee joint kinetics during a golf swing: influences of skill level and footwear. *The American Journal of Sports Medicine, 26*(2): 285-94

12. Gatt CJ, Pavol MJ, Parker RD, Grabiner MD (1999). A kinetic analysis of the knees during a golf swing. In: Farrally MR, Cochran AJ (Eds.), *Science and golf III. Proceedings of the 1998 World Scientific Congress of Golf*. Champaign, IL: Human Kinetics, 20-28.

13. Geisler PR (2001). Golf. In: Shamus E, Shamus J, editors. *Sports injury prevention and rehabilitation*. New York: McGraw-Hill, 185-225.

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

15. Jacobson BH, Stemm JD, Redus BS, Goldstein DF, Kolb T (2005). Center of Vertical Force and Swing Tempo in Selected Groups of Elite Collegiate Golfers. *The Sport Coaching Journal (serial online) 1*(2), (6 screens/inclusive page) Available from URL: www.sportsbalance.com/pdf/sport-coach-ncaa.pdf.

16. Kaneko Y, Sato F (1993). The optimization of golf swing and its application to the golf club design. In: *Proceedings of XIV International Symposium on International Society of Biomechanics*, Paris, 652-653.

17. Kawashima K, Meshizuka T, Takaeshita S (1999). A kinematic analysis of foot force exerted on the soles during the golf swing among skilled and unskilled golfers. In: Farrally MR, Cochran AJ (Eds.), *Science and golf III. Proceedings of the 1998 World Scientific Congress of Golf*. Champaign, IL: Human Kinetics, 40-45.

18. Koenig G, Tamres M, Mann RW (1994). The biomechanics of the shoe-ground interaction in golf. In: Cochran AJ, Farrally MR (Eds.), *Science and golf II. Proceedings of the 1994 World Scientific Congress of Golf*. London: E & FN Spon, 40-45.

19. Koslow R (1994). Patterns of weight shift in the swings of beginning golfers. *Perceptual and Motor Skills, 79*: 1296-1298.

20. Mason BR, McGann B, Herbert R (1995). Biomechanical golf swing analysis. In: Bauer T (Ed.), *Proceedings of the XIII International Symposium for Biomechanics in Sport*, 67-70.

21. Milburn PD (1982). Summation of segmental velocities in the golf swing. *Medicine and Science in Sports and Exercise, 14*: 60-64.

22. Nagao N, Sawada Y (1973). A kinematic analysis in golf swing concerning driver shot and n_0 9 iron shot. *The Journal of Sports Medicine, 13*: 4-16.
23. Neal R (1998). Golf swing styles: A kinetic and 3D kinematic comparison. *Communication to the Australian Conference of Science and Medicine in Sport*. available at www.ausport.gov.au/fulltext/1998/acsm/smabs183.htm.
24. Neal RJ, Abernethy B, Moran MJ et al. (1990). The influence of club length and shot distance on the temporal characteristics of the swings of expert and novice golfers. In: Cochran AJ (Ed.), *Science and golf I. Proceedings of the First World Scientific Congress on Golf*. London: E & FN Spon, 36-42.
25. Neal RJ, Wilson BD (1985) 3D kinematics and kinetics of the golf swing. *International Journal of Sport Biomechanics, 1*: 221-232.
26. Okuda I, Armstrong CW, Tsunezumi H et al. (2002) Biomechanical analysis of professional golfer's swing: Hidemichi Tanaka. In: Thain E (Ed.), *Science and golf IV. Proceedings of the 2002 World Scientific Congress of Golf*. London: E & FN Spon, 19-27.
27. Richards J, Farrel M, Kent J, Kraft R (1985) Weight transfer patterns during the golf swing. *Research Quarterly for Exercise and Sport, 4*: 361-365.
28. Robinson RL (1994). A study of the correlation between swing characteristics and clubhead velocity. In: Cochran AJ, Farrally MR (Eds.), *Science and golf II: Proceedings of the 1994 World Scientific Congress of Golf*. London: E & FN Spon, 84-90.
29. Vaughan CL (1982). A three-dimensional analysis of the forces and torques applied by a golfer during the downswing. In: Morecki A, Fidelus K, Kedzior K et al. (Eds.), *Biomechanics VII-B*. Baltimore, MD: University Park Press, 325-331.
30. Wallace ES, Graham D, Bleakley EW (1990). Foot to ground pressure patterns during the golf drive: a case study involving a low handicap player and a high handicap player. In: Cochran AJ (Ed.), *Science and Golf: Proceedings of the First World Scientific Congress of Golf*. London: E & FN Spon, 25-29.
31. Wallace ES, Grimshaw PN, Ashford RL (1994). Discrete pressure profiles of the feet and weight transfer patterns during the golf swing. In: Cochran AJ, Farrally MR (Eds.), *Science and golf II. Proceedings of the 1994 World Scientific Congress of Golf*. London: E & FN Spon, 26-32
32. Williams KR, Cavanagh PR (1983) The mechanics of foot action during the golf swing and implications for shoe design. *Medicine and Science in Sports and Exercise, 15*: 247-55.