Effect of Horizontal Ground Reaction Forces during the Golf Swing: Implications for the Development of Technical Solutions of Golf Swing Analysis †

Maxime Bourgain [1,2,*], Christophe Sauret [2], Grégoire Prum [2,3], Laura Valdes-Tamayo [2], Olivier Rouillon [4], Patricia Thoreux [2,5] and Philippe Rouch [2]

1 EPF Graduate School of Engineers, 92330, Sceaux, France
2 Institut de Biomécanique Humaine Georges Charpak, Arts et Métiers ParisTech, 75013, Paris, France; christophe.sauret@ensam.eu (C.S.); gregoire.prum@chu-rouen.fr (G.P.); laura.valdes@ensam.eu (L.V.-T.); patricia.thoreux@aphp.fr (P.T.); philippe.rouch@ensam.eu (P.R.)
3 Physical and Rehabilitation Medicine, Rouen University Hospital, 76000 Rouen, France
4 Fédération Française de Golf, 92300, Levallois Perret, France; medecin.federal@ffgolf.org
5 Hôpital Avicenne, Université Paris 13, Sorbonne Paris-Cité, AP-HP, 93017 Bobigny, France
* Correspondence: maxime.bourgain@ensam.eu; Tel.: +33-01-41-13-01-92
† Presented at the 13th conference of the International Sports Engineering Association, Online, 22–26 June 2020.

Abstract: The swing is a key movement for golf. Its in-field performance could be estimated by embedded technologies, but often only vertical ground reaction forces (VGRF) are estimated. However, as the swing plane is inclined, horizontal ground reaction forces (HGRF) are expected to contribute to the increase of the club angular velocity. Thus, this study aimed at investigating the role of the HGRF during the golf swing. Twenty-eight golf players were recruited and performed 10 swings with their own driver club, in a motion analysis laboratory, equipped with a full body marker set. Ground reaction forces (GRF) were measured with force-plates. A multibody kinematic optimization was performed with a full body model to estimate the instantaneous location of the golfer's center of mass (CoM). Moments created by the GRF at the CoM were investigated. Results showed that horizontal forces should not be neglected regarding to VGRF because of their lever arm. Analyzing golf swing with only VGRF appeared not enough and further technological developments are still needed to ecologically measure other components.

Keywords: GRF; multi-body kinematic optimization; sport biomechanics; sport performance; golf swing

---

1. Introduction

Golf is a sport played all around the world, in which the swing is a key movement. The golf swing in commonly composed of four phases: (1) the address; (2) the backswing; (3) the downswing; and (4) the follow-through. During this movement, the lead side is the closest to the target and the opposite side is called the trail side.

During the last decades, the golf swing has been widely studied in laboratory and several qualitative and quantitative parameters were proposed to explain the swing performance, such as the X-factor [1] and the kinematic sequence [2]. However, those methods were proved to be highly dependent upon the model chosen [3,4]. To ease the appropriation of those concepts by coaches and golfers, some in-field devices were developed using videos, inertial measurement units, or weight-bearing measurement devices such as Kvest or Swing Catalyst.

In laboratory, some studies had investigated the influence of ground reactions forces (GRF) on swing performance but most of them had only considered the vertical component of the GRF. More especially, they investigated the weight transfer [5,6] which occurs from the trail to lead sides during the downswing, with a peak before the ball impact [7]. However, only a few studies have investigated the role of the GRF horizontal components (HGRF) and showed that HGRF amplitude increases with ball flight distance but not their direction in the horizontal plane [8]. For several years, in-field GRF measurements devices have been proposed to golfers and coaches based on pressure insoles and weight-bearing systems which are able to capture the GRF normal component to the foot or the GRF vertical component (VGRF), respectively. More recently, some devices allowing the measurement of HGRF were also proposed but at a much higher cost. In order to analyze the benefice of 3D measurement devices in comparison to 1D components, this study aimed at comparing the contribution of the different GRF components on the motor moment responsible for the club head acceleration during the downswing phase.

2. Materials and Methods

Twenty eight male volunteers were recruited to participate in this study and were split into two groups: amateur golfers (GA, n = 19), with an average handicap of 15 (SD: 6 range: 1–25), and professional golfers (GPro, n = 9). They were asked to use their own golf shoes, driver club, and gloves. The protocol, described below, was ethically approved by an independent committee (2015-A01760-49, Ile de France X) and each volunteer was informed and signed an informed consent form prior to the experiments.

Acquisitions were performed in an indoor motion analysis laboratory composed of 12 cameras (Vicon system, Oxford metrics, UK; 200 Hz) and two 3D force plates (OR6, AMTI, 1200 Hz) covered with artificial turf. The global reference frame was defined at the address as the z-axis vertically pointing upward; the y-axis horizontally pointing from the back to the front of the golfer; and the x-axis horizontally pointing opposite to the target. The golf performance was considered as the clubhead speed at impact as it is commonly done in laboratory studies. It was assessed with a dedicated golf launch monitor (Trackman 3, Trackman, USA) measuring the club head velocity at the ball impact. A net was positioned 6 m away from the golfer to stop the ball.

After performing their own warm-up routine, subjects were equipped with a full body marker set of 88 reflective markers [9] and a static trial acquisition was performed with the subject in the classical anatomic position. Three markers were added on the club: 1 for the head and 2 for the shaft. After being accustomed to the equipment, they were asked to perform 10 swings, as natural as possible, with one foot on each force-plate.

For each subject, only the best swing was selected, following the criteria of the highest club head velocity at the ball impact. A biomechanical full body model [9] was first scaled to fit the subject anthropometry using the markers position during the static acquisition and the subject total mass. The segmental kinematics was then obtained using a multibody kinematics optimization algorithm implemented in OpenSim Software [10]. For each instant, the location of the golfer global center of mass (CoM) was computed as the barycenter of all the segments CoM locations.

The functional swing plane was computed as the plane minimizing the squared distances of the clubhead marker position during mid-downswing to impact, according to a current consensus [11,12]. The mid-downswing was computed when the shaft markers define a horizontal line. The instant of the ball impact was defined as when the clubhead was the closest to the initial position at the address.

The GRF were expressed at the center of pressure (CoP) on the horizontal plane for each force-plate, directly with Nexus software procedure. All measured GRF were divided by the subject mass for data normalization. For the lead and trail feet, the mean, standard deviation, minimum, and maximal values of HGRF and VGRF were computed over the downswing. Then, the motor moment (MMot) was computed as the global moment produced by the GRF of both feet at the CoM and following the direction perpendicular to the swing plane [13]. The positive and negative contribution of both HGRF and VGRF were computed for both lead and trail sides. Linear correlation with club head speed was computed with a Pearson test performed on Matlab 2019a. Correlations were considered as significant for Pearson coefficient out of the range from −0.7 to 0.7. The moment lever arm for all GRF components to MMot contribution were computed, they were considered positive if they generated a positive MMot and negative if they negatively contributed to MMot.

3. Results

Differences between amateurs and professionals regarding their swing performance and downswing duration were reported in Table 1. The GPro mean club head speed was unsurprisingly higher than those of GA but with some overlap between the two groups. Dealing with downswing duration, there was no significant difference between groups and the values were consistent with other studies [14].

Table 1. Differences between professional golfers (GPro) and amateur golfers (GA) for club head velocity at impact, downswing duration, and GRF. VRGF and HGRF were divided by the subject weight and only the maximum value for each subject was taken into account in this table.

	GPro	**GA**	**Overall**
Club head velocity (m/s) Mean (standard deviation)	48.5 (2.6)	40.5 (4.3)	43.1 (5.3)
Downswing duration (s)	0.26 (0.02)	0.28 (0.02)	0.27 (0.04)
Maximum VGRF (N/N) Mean (SD) lead/trail	1.181(0.285) 0.642(0.070)	1.241(0.206) 0.696(0.136)	1.222(0.230) 0.679(0.120)
Maximum HGRF(N/N) Mean (SD) lead/trail	0.158(0.06) 0.131(0.04)	0.186(0.08) 0.127(0.07)	0.177(0.07) 0.128(0.06)

The correlation between the mean and the maximum values of each component of the GRF and the club head speed presented no strong correlation for each population and the overall population. Overall, for trail and lead sides respectively, the maximum of the mean value of VGRF were −67% and 101%, for HGRF antero-posterior: 23% and −21%, and for HGRF medio-lateral: 18% and −17%. All golfers had a peak of VGRF before impact, in accordance to [7], except one professional golfer. However, GPro had no higher maxima of VGRF or HGRF than GA, according to Table 1.

The highest lever arm was computed for trail HGRF, with an overall maximum of 0.91 m. VGRF lever arm were smaller with an overall maximum of 0.28 m. Interestingly, on average over all golfers, the lever arm of VGRF were 0.04 m (SD: 0.02 m) and 0.03 m (SD: 0.02 m) for trail and lead sides, respectively. However, amplitude of lever arms for HGRF were higher, with average values of 0.46 (SD: 0.31 m) and 1.13 m (SD: 0.24 m) for the trail and lead sides, respectively.

The average values of MMot are reported at Figure 1a. The correlation coefficient with club head speed is 0.83. Contributions of HGRF and VGRF of both feet to MMot are reported at Figure 1b, ordered by club head speed (best on the right). Vertical leading force contribution to the moment (Vert L) was the highest positive contribution (37% of the whole amplitude of MMot, on average). However, trail foot HGRF (Horiz T) positively contributed to MMot production (26% on average). Additionally, trail VGRF (Vert T) and lead VGRF (Vert L), but also trail HGRF (Horiz T), contributions were of the same order of magnitude in absolute values. Interestingly, the lead HGRF (Horiz L) contribution was either positive or negative depending of the golfer.

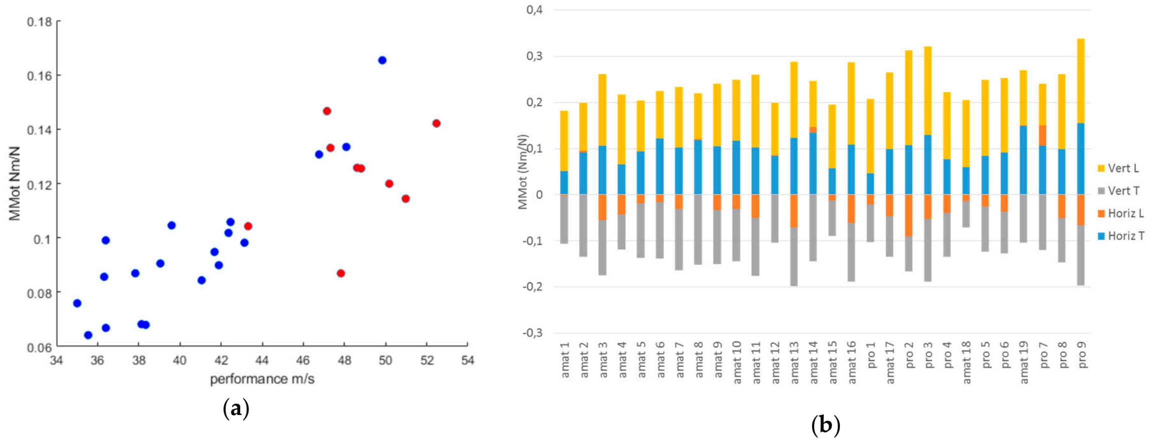

Figure 1. (**a**) Normalized motor moment (MMot) production with respect to the club head speed at impact: blue dots are for GA and red dots are for GPro. (**b**) Cumulative histograms of the motor moment production for the GPro group, vertical leading moment (yellow), vertical trail moment (grey), horizontal leading moment (orange), and horizontal trail moment (blue).

Figures 2 and 3 presents the MMot production during the downswing of the golfer with the highest club head speed (52.5 m/s). According to Figure 2a, components could be positive, negative, or change sign during the downswing, for the lead VGRF. According to Figure 2b, HGRF allow to maintain a high value of motor moment when the vertical contribution is decreasing.

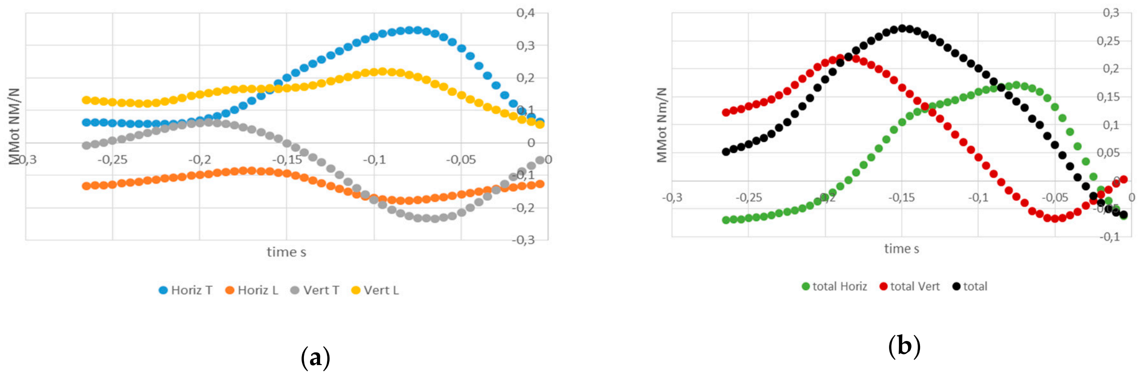

Figure 2. Time course, during the downswing, for the best golfer, and normalized by the weight of (**a**) the 4 contributions of MMot (both feet and both directions); and (**b**) the global horizontal and vertical contributions.

It must be noticed that as the lines of action of the different GRF were not collinear with the vertical (z+) direction, the orientation of the lever arm of the forces regarding the center of mass permitted to generate positive or negative MMot as it is represented in Figures 2 and 3. In Figure 3a, for the frontal view, the leading side produced a higher positive MMot, whereas the non-leading side had a small lever arm and produced a positive MMot. However, on the upward view, both sides contributed to produce a positive MMot. In Figure 3b, the same kind of pattern occurs. In Figure 3c, in the frontal view, the leading side continued to produce a positive MMot but with a small lever arm, whereas the non-leading side produced a negative MMot. In the upward view, both sides continues to produce a positive MMot.

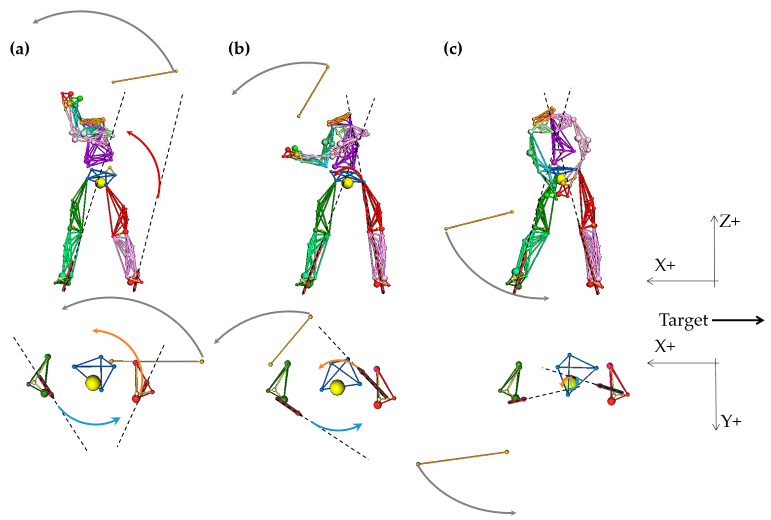

Figure 3. Illustration of the MMot production during the downswing for the best golfer. Frontal and upward views (**a**) at the top of backswing, (**b**) at the early downswing, and (**c**) at the late downswing. Dotted black line: line of action of each ground reaction force (GRF); gray arc arrow: club head movement; red arc arrow: MMot of the lead side in the frontal view; blue arc arrow: MMot in the horizontal plane produced by the non-leading side; and orange arc arrow: MMot in the horizontal plane produced by the leading side. Green markers: trail leg; and red markers: leading leg. Yellow ball: center of mass (CoM).

4. Discussion

There were no direct strong correlations between GRF components and club head speed. However, all components contributed to the MMot either positively or negatively. When analyzing the GRF orientation regarding the CoM, the HGRF may play an important role for club speed production. This is in accordance with a previous study [8] which highlighted the importance of the angle of GRF in the horizontal plane. More particularly, in the present study, it was shown that both the vertical and horizontal GRF components may produce a negative moment, which in turn contributes to slow down the global movement. Meister et al. also presented a parameter taking into account the horizontal forces but estimated the moment computed on the CoP and projected to the vertical axis [15]. They measured an increase of this moment with the club head speed. However, as the functional swing plane is inclined, a projection on the direction perpendicular to the functional swing plane could permit to identify the efficient part of the moment production.

Motor moment contributed to explain what seems to be one optimal coordination of GRF during the swing. However, it seemed inevitable that some components remain negative, which may help to keep stability. The only global difference between golfers was regarding the lead HGRF, which could be positive or negative regardless of the golfer clubhead speed. However, as only one swing was analyzed per subject, the intra-subject repeatability should be investigated.

GRF lever arms were three times higher for HGRF than VGRF. The lever arm of the VGRF was about the half of the between feet distance, but the one of the HGRF is about the length of the leg (distance foot-CoM). Thus, even if forces in the horizontal plane were smaller, their contribution to the MMot production may be high. Therefore, measuring all three components of both feet GRF appeared essential as well as the accurate assessment of the CoM position.

5. Conclusions

This study shows that the motor moment could be an indicator that may help to understand the swing efficiency. However, it necessitates to assess both the 3D components of the trail and lead foot ground reaction forces and their respective CoP location; as well as the global center of mass.

The present study highlighted the importance of taking into account both the VGRF and HGRF to understand the swing performance. Indeed, the use of HGRF may be a strategical difference within golfers. However, up to now HGRF has been often neglected when using embedded systems. Thus, attention should be paid when analyzing golf swing with only VGRF estimations and further technological developments are still needed to measure those components in the field associated to the center of mass location.

Acknowledgments: Authors would like to thanks all the volunteers who participated in this study, TrackMan to borrow its system, and the French Federation of Golf for its logistic to help recruiting the volunteers.

Conflicts of Interest: The authors declare no conflict of interest. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

1. Cheetham, P.J.; Martin, P.E.; Mottram, R.E.; St. Laurent, B.F. The importance of stretching the "X-Factor" in the downswing of golf: The "X-Factor Stretch". In Proceedings of the International Conference on Sport Science, Sport Medicine and Physical Education, Brisbane, Australia, 7–13 September 2000.
2. Tinmark, F.; Hellström, J.; Halvorsen, K.; Thorstensson, A. Elite golfers' kinematic sequence in full-swing and partial swing shots. *Sports Biomech.* **2010**, *9*, 236–244, doi:10.1080/14763141.2010.535842.
3. Marsan, T.; Thoreux, P.; Bourgain, M.; Rouillon, O.; Rouch, P.; Sauret, C. Biomechanical analysis of the golf swing: Methodological effect of angular velocity component on the identification of the kinematic sequence. *Acta Bioeng. Biomech.* **2019**, *21*, doi:10.5277/ABB-01318-2019-02.
4. Kwon, Y.-H.; Han, K.H.; Como, C.; Lee, S.; Singhal, K. Validity of the X-factor computation methods and relationship between the X-factor parameters and clubhead velocity in skilled golfers. *Sports Biomech.* **2013**, *12*, 231–246, doi:10.1080/14763141.2013.771896.
5. Chu, Y.; Sell, T.C.; Lephart, S.M. The relationship between biomechanical variables and driving performance during the golf swing. *J. Sports Sci.* **2010**, *28*, 1251–1259, doi:10.1080/02640414.2010.507249.
6. Stastny, P.; Maszczyk, A.; Tomankova, K.; Kubovy, P.; Richtrova, M.; Otahal, J.; Cichoň, R.; Mostowik, A.; Zmijewski, P.; Cięszczyk, P. Kinetic and Kinematic Differences in a Golf Swing in One and Both Lower Limb Amputees. *J. Hum. Kinet.* **2015**, *48*, 33–41, doi:10.1515/hukin-2015-0089.
7. Wang, J.-J.; Yang, P.-F.; Ho, W.-H.; Shiang, T.-Y. Determine an effective golf swing by swing speed and impact precision tests. *J. Sport Health Sci.* **2015**, *4*, 244–249, doi:10.1016/j.jshs.2014.12.003.
8. McNitt-Gray, J.L.; Munaretto, J.; Zaferiou, A.; Requejo, P.S.; Flashner, H. Regulation of reaction forces during the golf swing. *Sports Biomech.* **2013**, *12*, 121–131, doi:10.1080/14763141.2012.738699.
9. Bourgain, M.; Hybois, S.; Thoreux, P.; Rouillon, O.; Rouch, P.; Sauret, C. Effect of shoulder model complexity in upper-body kinematics analysis of the golf swing. *J. Biomech.* **2018**, *75*, 154–158, doi:10.1016/j.jbiomech.2018.04.025.
10. Delp, S.L.; Anderson, F.C.; Arnold, A.S.; Loan, P.; Habib, A.; John, C.T.; Guendelman, E.; Thelen, D.G. OpenSim open-source software to create and analyze dynamic simulations of movement. *IEEE Trans. Bio-Med. Eng.* **2007**, *54*, 1940–1950, doi:10.1109/TBME.2007.901024.
11. Morrison, A.; McGrath, D.; Wallace, E.S. The relationship between the golf swing plane and ball impact characteristics using trajectory ellipse fitting. *J. Sports Sci.* **2017**, 1–8, doi:10.1080/02640414.2017.1303187.
12. Kwon, Y.-H.; Como, C.S.; Singhal, K.; Lee, S.; Han, K.H. Assessment of planarity of the golf swing based on the functional swing plane of the clubhead and motion planes of the body points. *Sports Biomech.* **2012**, *11*, 127–148, doi:10.1080/14763141.2012.660799.
13. Bourgain, M.; Sauret, C.; Rouillon, O.; Thoreux, P.; Rouch, P. Contribution of vertical and horizontal components of ground reaction forces on global motor moment during a golf swing: A preliminary study. *Comput. Methods Biomech. Biomed. Eng.* **2017**, *20*, 29–30, doi:10.1080/10255842.2017.1382845.
14. Egret, C.; Dujardin, F.; Weber, J.; Chollet, D. 3-D kinematic analysis of the golf swings of expert and experienced golfers. *J. Hum. Mov. Stud.* **2004**, *47*, 193–204.
15. Meister, D.W.; Ladd, A.L.; Butler, E.E.; Zhao, B.; Rogers, A.P.; Ray, C.J.; Rose, J. Rotational biomechanics of the elite golf swing: Benchmarks for amateurs. *J. Appl. Biomech.* **2011**, *27*, 242–251.