3D Motion Analysis of Golf Swings

Development and validation of a golf-specific test set-up

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Abstract—The aim of this paper is to describe applications and limitations of 3D motion analysis in golfing. The following five golf-specific error sources were identified: Occlusion of markers, high velocity of hands, club and ball, inaccuracies in the determination of body segment rotations, vibrations at impact, accumulation of high numbers of markers in a small area. A specific test set-up that minimizes the effect of these error sources was designed (12 camera motion analysis system, f=250 Hz, accuracy < 1.5mm, some markers were placed on sticks). In order to validate this set-up, additional devices were used to determine clubhead velocities, ball velocities and launch angles for 55 golf swings performed by two experienced golf players. Results indicate that this set-up can help to reduce these errors. However, markers placed on extension sticks were subject to significant vibrations and need to be constructed differently in the future. A high correlation of three parameters calculated from 3D motion capture data with parameters from alternative devices indicates that these values can be determined accurately by the 3D motion capture set-up presented.

3D Motion Analysis, Golf, Marker- set, wand markers

I. INTRODUCTION

New technologies allow increasingly complex models and simulations of human motion, e.g. by applying methods of inverse dynamic modeling and forward dynamic simulation. As golfing is a popular sports activity, and the golf swing is a complex full body movement, it seems reasonable to apply these methods to gain new insights into the mechanics and biomechanics of the golf swing, e.g. in order to estimate the load on internal anatomical structures, to analyze the efficiency of individual swings, or to evaluate new golf club design concepts. Usually, the input data of these models includes the 3D kinematics of the movement, obtained by 3D motion analysis. Therefore, it has to be assured that the input data from 3D motion analysis is accurate before 3D models of the golf swing can be constructed and used for further studies. This paper first summarizes the recent development of 3D motion analysis of the golf swing, and secondly, it describes golfspecific error sources in 3D motion analysis, and possibilities to minimize these errors are validated.

A. Literature Review

In this brief summary of a literature review of applications of 3D motion analysis in golfing, emphasis is given to optical analyses that include the body movement of the player. Several studies that focus on the motion of the club in 3D space or that utilize other, non-optical observation methods (such as gyroscopes or goniometers) were found but are not included here.

According to their literature review, Neal and Wilson [1] were second to report of a 3D study on golf kinetics. Utilizing two cameras (frame rate 294 Hz), they focused on the motion of forearm, wrist and club to investigate whether this system could be modeled as a double pendulum. One of their findings was that the trajectory of the club during the downswing is not planar. Therefore, previous 2D studies seem to be too simplistic. Other studies included the observation of more body landmarks in order to obtain information on the full body kinematics ([2], [3], [4]). Due to technical limitations in processing data from multiple cameras, 3D coordinates of the body landmarks were calculated by using only two cameras in these early studies. Therefore, it can be questioned whether the methods described could be suitable to obtain useful input data for complex, full body models. Recently, more cameras (up to 6) were used, but in some studies the frame rates were relatively low (e. g. [5]), and in others, the number of markers under observation seems to be too small to be sufficient for full body modeling ([6], [7], [8]). Remarkably, in 1994, Nesbit et al. ([9]) already reported a reconstruction of the 3D motion of torso, hips, shoulders and wrists by using four cameras and the creation of a 3D-full body model of a golfer swinging a club, but no detailed information on their data acquisition methods are given. References [10] and [11] describe how 3D motion analysis was used to create 3D visualizations of their data, but the researchers only focused on kinematic analyses (e.g. stance, knee angle, trunk inclination, hip angle, shoulder angle) and did not create a 3D model with actual physical properties (mass, inertia) based on their data, so their results are not suitable to calculate internal loads.

In summary, only few studies that included a 3D representation of the full body of the golfer could be found. Only in one study ([9]) 3D motion analysis was used to simulate the swing using a model with physical properties, but no details on the set-up used is available (e. g. marker positions, frame rate, cameras positions). Apparently no standard procedures exist that allow accurate collection of 3D data in order to create 3D models of golf swings. Therefore, the first aim of this paper is to describe necessary considerations before 3D motion capture data can be used for full body modeling of the golf swing.

B. Golf-specific problems in 3D motion analysis

Cappozzo et al. ([12]) showed that, in 3D motion analysis, calculated rotations of body segments about their longitudinal axes can be unreliable. In golfing, even small rotations of the wrists can influence the clubhead orientation significantly due to the length of the golf club. Therefore, inaccuracies in segmental rotation assessment need to be reduced to a minimum to avoid significant errors when the swing is to be modeled. Another problem arises from the high velocity of the player's hands and the club during the downswing. For advanced players, the clubhead velocity can be as high as 45 m/s ([5]). Not only is the reconstruction of 3D coordinates of an object moving with this velocity difficult if the frame rate is too low, but also the velocity of the clubhead and the hands can change rapidly during ball impact. If the frame rate is too low it becomes likely that velocity peaks are not registered by the measuring system (Nyquist-Shannon sampling theorem). Furthermore, forces exchanged between ball and club and between club and player during the impact of ball and clubhead are very high, which causes problems in marker attachment to the clubhead and enhances vibrations of body markers. Finally, the body pose of the golfer can cause problems of occlusion and makes identification of some of the markers more difficult than in common applications of 3D motion analysis, such as gait analysis, where the distal ends of the arms are free to move. During some phases of the swing the arms can occlude trunk markers placed on the clavicle and sternum. Because both the left and right forearm and hand are positioned close to each other during the entire swing, a high number of markers are accumulated in a small volume if the markers are placed according to standard marker-sets. Both automatic and manual marker identification and tracking become difficult.

In summary, the following golf-specific key problems can be identified from theoretical considerations on typical marker placements and the characteristics of a typical golf swing:

- a) Occlusions of markers
- b) High velocities of hands, club, and ball
- c) Inaccuracies in segment rotation
- d) Vibrations at impact
- e) Accumulation of markers in a small volume

II. A GOLF-SPECIFIC MOTION CAPTURE SET-UP

A. Design of the set-up

A specific test set-up was designed to address and avoid the previously described problems a)-e).

In general, overall accuracy of 3D motion analysis can be increased and occlusions can be avoided by using a high number of cameras. Therefore, a 12-camera VICON v8i system (Oxford Metrics Ltd., Oxford, England) was utilized in this test. In order to address problem b), the system was set to operate at a frequency of 250 Hz, which is a higher frequency than in all multiple cameras studies found in the literature.

A total number of 48 markers was placed in anatomical positions. Following a suggestion by BRG Inc. ([13]), eight markers were placed on 100 mm sticks ("wand markers", one on each segment of the limbs, see Figure 2.). The purpose of these markers is to increase the distance between the marker and the longitudinal rotation axis of the segment, in order to enhance the accuracy of the calculation of segment rotations (i.e. internal/external (legs, upper arms) and pronation/ supination (forearms)). One additional marker was placed on the surface of each limb segment as close as possible to the base of the markers on the extension sticks in order to allow observation of the movement of the wand marker relative to the segment itself, especially during the impact phase. Another difference of the marker set proposed by [13] to standard marker-sets lies in the reduced number of hand and wrist markers. Instead of one hand marker and two wrist markers, only one single wrist marker is used as the hands remain attached to the club at all times during the swing. This configuration might help to avoid the problem of accumulation of many markers in the hand/ wrist area.

Two markers were placed on the golf club: one 300 mm from the center of the hands in address position and one at the lower end of the shaft. Instead of a previously reported placement of a standard marker on the outside of the shaft ([11], see Figure 1. a), it was decided to use a special marker that surrounds the shaft. In this position, the marker does not point to the floor during the backswing and is more likely to be visible to the majority of the cameras.



Figure 1. Comparison of initial (a) and modified (b) spherical clubhead marker



Figure 2. Dimensions and construction of wand marker used. Each marker consisted of a silicone base plate, a hollow pipe and a rigid, hollow marker.



Figure 3. Set-up of photo sensors and radar device that were used to determine the clubhead velocity, ball velocity and launch angle of the ball independently from the 3D motion capture system.

B. Validation of the set-up

In order to validate the test set-up suggested in this paper, two advanced golfers performed 55 golf swings each (self reported handicap: 8.5 ±1.5, age: 22 ±0 years , height: 1.83 ± 0.2 m, weight: 81.5 ± 2 kg). These swings were recorded by the previously described motion capture system. Additionally, a commercially available radar device ("Swingmate" Beltronics Inc., USA) was used to determine the clubhead velocity at impact. A board with two vertical rows of photo sensors was designed in order to measure the velocity and the launch angle of the ball and was placed next to the player (see Figure 3.). Signals from the photo sensors were recorded with a sample rate of 3750 Hz. Each row of photo sensors triggered a signal when the ball passed it, providing two signals for the calculation of the initial ball velocity. Additionally, the height of the photo sensor triggered in each row allowed to determine the launch angle of the ball.

III. RESULTS OF SET-UP VALIDATION

A. Marker set

The time spent on data processing could be reduced significantly by using the improved marker-set. Identification of the reduced number of wrist and hand markers became more simple and reliable. Furthermore, the modified clubhead marker was identified more easily by the Motion Capture system. It was also easy to identify the markers placed on sticks away from the body. In order to quantify possible

vibrations of these markers, the angle between each wand marker and a corresponding skin marker placed close to the base of the stick marker was calculated for the humerus, thigh and shank segments for some of the trials (see Figure 4. for definition of the angle calculated). As can be seen from Figure 4., the angle between a line from each of these markers to the longitudinal axis of the corresponding segment would remain constant at all times if both markers were rigidly connected to the same skin area. Because the skin marker and the base of the wand marker were placed close together it could be assumed that both markers were subject to the same skin movement artifact. However, it can be seen from Figure 5. that significant movement of the wand markers relative to the respective segment occurred. The patterns of these movements for each marker were similar throughout the trials. The range of the movement of the wand markers were smaller for the leg markers (e. g. thigh segment: 8°-18°) than for the arm markers and smaller for the left side of the body than for the right. Greatest movements were observed for the markers on the right humerus (up to 65° relative to the skin marker).



Figure 4. Definition of a wand marker vibration measure. The angle is exaggerated for better illustration. Skin marker and wand marker were placed as close to each other as possible, so it could be assumed that artefacts due to skin movement were the same for both markers. If both remained in the same position relative to the segment axis, the angle would remain constant.



Figure 5. Examples for the vibration of wand markers relative to a skin marker placed close to the base of the respective wand marker. See Figure 4. for definition of the angle illustrated.

Table 1: Comparison of 3D motion capture results with results from				
alternative measurement devices				
Parameter	Number of swings compared	Mean 3D motion capture	Mean reference device	Correlation Coefficient
Clubhead Vel. ^a	106	42.3 m/s	47.6 m/s	0.72
Ball Velocity ^a	71	63 m/s	65 m/s	0.63
Launch Angle ^b	74	14.1°	12.6°	0.94
Reference measurements: a. photo cells; b. "Swingmate" radar device				

Reference measurements, a. photo cens, b. Swingmate radar dev

B. Clubhead velocity and ball launch characteristics

Because the two subjects in this study were comparable both in their anthropometrics and their performance, their results were pooled for a comparison of the 3D motion capture system with the reference devices used.

As can be seen from Table 1, significant differences between mean clubhead and ball velocities measured by the 3D motion capture system and the reference devices were observed. However, a paired comparison of the results from the different devices yielded high correlations between the results, indicating that systematic errors caused the differences. These systematic errors were most likely caused by differences in how data was acquired by the different systems. As for the clubhead velocity, the radar device recorded higher peak clubhead velocities than the 3D motion analysis system. These differences were most likely caused by different reference points used by the two systems: the marker used for velocity calculation by the 3D motion capture system was placed on the shaft of the golf club with an offset to the clubhead (see Figure 1. a), whereas the radar device measured the velocity of the actual clubhead. Because of this offset the clubhead marker moved slightly slower than the clubhead and therefore, velocities recorded by the 3D motion capture system were slower. For the ball velocity, the differences between velocities measured by the 3D motion capture system and by the photo cell board are most likely caused by the fact that the photo cells recorded the ball velocity during the initial 0.5 m of the ball trajectory, whereas the ball velocity values calculated from 3D motion capture data represent an average of the velocity during the first 8 frames recorded of the ball flight. Within these frames the ball slows down, causing slightly smaller ball velocity readings from the 3D motion capture system.

IV. CONCLUSION

In most areas, the golf-specific modifications of the motion analysis procedure yielded improvements. Easier identification of the markers in the forearm/ wrist area made data processing easier and more reliable. The modified clubhead marker and the increased frame rate of the motion capture system increased the visibility of the clubhead significantly. However, the wand markers used were insufficient and either need to be constructed in a different way to become more resistant to vibrations or need to be replaced by skin markers. A comparison of swing parameters recorded by the 3D motion capture system and two reference systems showed significant differences between the results from the different systems. However, correlation of the data sets were high, indicating that systematic errors due to the different measurement principles caused these differences. This confirms that measurements obtained by one system can be compared to other measurements from the same system. If measurements from different systems are to be compared, however, the offset between the values from each system has to be taken into consideration.

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