

Motion Capture in Golf

Ian Wright

TaylorMade – adidas Golf
5545 Fermi Court, Carlsbad, California, 92008, USA.
E-mail: ian.wright@tmag.com

ABSTRACT

Motion capture has been used extensively to study the golf swing in the laboratory. As motion capture technology has become more sophisticated and less expensive, the number of research studies has increased as has the scope of these research studies. Motion capture technology has become so accessible that it is now being used outside of the laboratory, for golf instruction, coaching and club fitting. The use of this technology can enhance the teaching or club fitting experience, and will likely lead to increased understanding of the biomechanics of the golf swing.

Key words: Biomechanics, Club Fitting, Golf Swing, Motion Capture

INTRODUCTION

The golf swing is scrutinized extensively. When it comes to the golf swing, it seems that many golf instructors, coaches, players and spectators fancy themselves as experts in the analysis of movement, and have plenty to say about most any golf swing they observe. Many books on golf instruction focus extensively on the positions that the player and his or her club achieve throughout the swing. Modern tools, from photography, film, video, optical, magnetic and inertial motion measurement seem to facilitate and fuel this desire to scrutinize and dissect the golf swing. Historically, motion capture technology was prohibitively expensive and difficult to use, restricting its use to the laboratory and to the research scientist. As these technologies get less expensive and easier to use, the use of motion capture technology is spreading. It is now in use in commercial settings for golf instruction and club fitting, and is being used by increasingly large numbers of golf instructors on a growing number of players.

For researchers who have not had access to motion capture facilities in the past, they are increasingly becoming accessible in golf, and many people who have had no

experience in motion capture, such as golf instructors and coaches, are now being put into a position where they can use this equipment. Therefore, it is important for them to learn more about motion capture and how it can be used in golf instruction, coaching and club fitting.

Motion capture could be defined in many ways. Arguably, any observation of movement is “motion capture.” For the purposes of this paper, motion capture is limited to the quantification of positions and orientations of the player and/or his or her equipment over time. Systems that track the movement of the golf ball are not included. There is an assortment of technologies that can be used for motion capture. In this paper, several will be discussed. However, the greatest portion of this paper will be dedicated to optical motion-capture methods, with which this author has the most experience.

This is not strictly a review article, nor is it detailed description of a study or a collection of studies. Rather, it is meant to be a relatively informal introduction to the use of motion capture in golf.

The objectives of this paper are to:

- Outline some of the motion capture methods that have been used historically in the study of the golf swing
- Outline some motion capture methods currently available and in use commercially for golf swing research and instruction
- Describe in detail the MATT system, the motion capture technology co-developed by TaylorMade-adidas Golf for club fitting

GOLF SWING MOTION CAPTURE IN RESEARCH LITERATURE

PLANAR KINEMATICS

Some of the earliest studies that quantified the kinematics of the golf swing limited their investigations to movements in a single plane. Arguably, much movement of the arms and club occurs mostly in a single plane. So by positioning a camera roughly perpendicular to that plane, one can observe a lot of the salient features of the golf swing. Historically, when the use of computers for digitization and calculation of the movement was limited or non-existent, limiting one’s investigation to a single camera was very practical. Perhaps the first such study was Williams [1], who used one, 100 hz stroboscopic camera (a long film exposure with multiple short flashes of light) to capture the hand and club kinematics of Bobby Jones’ swing. Cooper et al. [2] used a high-speed camera running at 200 frames per second to look at the golf swing of 5 skilled players, and concluded that the golf swing exhibited a proximal-to-distal sequencing of movement. Milburn [3] used a single camera running at 300 frames per second to also look at 5 skilled players, also to examine the timing of the movements of the golf swing. Studies by Abernethy et al. [4] and Neal et al. [5] used a single camera running at 200 frames per second in combination with EMG to look for differences in the temporal aspects of the swings of 5 skilled and 5 novice players. The use of a single camera may be limited in its use for detailed examination of a movement that is not happening entirely in a single plane, but is likely sufficient for examining questions of timing as in these studies.

Van Geluwe et al. [6] used a single high-speed camera running at 500 frames per second to try to detect changes in swing kinematics between steel and graphite shafts. That study was noteworthy for the relatively large number of subjects examined (38 male and 13 female players).

THREE DIMENSIONAL KINEMATICS OF THE CLUB AND ARMS

To use more than one camera to reconstruct the three dimensional kinematics of the golf swing is a big step up in experimental and data processing complexity. To limit the complexity, several research studies restricted their focus to the movement of the club, or the club and the arms. Motion capture is made simpler if fewer markers and fewer bodies are being tracked. In the case of the golf swing, if only the club is being tracked, then camera placement can be simplified (being predominantly in front of the player), as the occlusion of the view of the club by the body is minimal. One such study that made an effort to examine the kinematics of the golf club in three dimensions was Vaughan [7]. He used two orthogonal motion picture cameras running at 300 frames per second to look at the club movements of 4 players in an effort to do inverse dynamics to determine the forces the player must apply to the club.

Several papers from one group of researchers [8-13] used two (or more) cameras with longer exposures but multiple flashes to reconstruct the kinematics of the golf club. They used this method in attempts to categorize golf swings [8] and to identify differences between skilled and unskilled players [9]. They also used their method to understand the dynamic response of the shaft of the golf club [11] and difference of behaviour between different shafts [12]. They also used the method to observe the differences in kinematics caused by dramatic changes in club mass properties [13]. Much of this work will have depended upon hand digitization of images as well as using their own software for marker position reconstruction.

Several theoretical models used to explore the dynamics of the swing have been models that considered only the club and arms (such as that in Cochran and Stobbs [9]). Similarly, several experimental studies have examined the kinematics of the club and arms in isolation from the rest of the body. Neal et al. [10] used a Motion Analysis Corporation system to automate the digitization and marker tracking while attempting to study the dynamic interactions between the arms and club of 10 skilled players. Mizoguchi et al. [11] used four cameras to look at the club and left arm at 60 frames per second. They were trying to see how players responded to changes in club length. Coleman and Rankin [12] used two cameras running at 50 frames per second, digitized by hand to track the movement of the left shoulder, arm and club of 7 players. The purpose of their paper was to demonstrate that the movement of the left arm and club are not co-planar.

THREE DIMENSIONAL KINEMATICS OF THE PLAYER

To expand the study of the kinematics of the golf swing to include the player can add considerable complexity to the method. Perhaps the earliest study that reported this was that of Neal and Wilson [13], who used 2 cameras (294 frames per second) to look at 6 skilled subjects to get whole body (14 segment model) kinematics, plus the kinematics of the club and clubhead. With only two cameras, landmarks may not always have been in view. However, if digitization is done by hand, estimates of

landmark locations can be made by the experimenter.

Other studies also used only two cameras to track three dimensional movement of the player. A study by McLaughlin and Best [14] used two cameras running at 50 frames per second to track 25 points including club, ball and player. They examined 10 players to look for kinematic measures that distinguished skilled from unskilled players. A study by Burden et al. [15] used two orthogonal high-speed cameras running at 50 frames per second to track hip and shoulder rotations during the golf swing of 8 players (sub-10 handicap). No attempt was made to track the club. One shot (longest drive) for each player was used only.

Nesbit et al. [16] described a method that used motion capture data to drive a dynamic simulation of the golf swing. They used four cameras at 180 frames per second to track torso, hips, shoulders and wrists in three dimensions. They reported that they limited their examination of the movement to body segments that were not bothered by marker occlusions. A contemporary study that used comparable motion capture methods was Lemak et al. [17]. They used a four-camera Motion Analysis Corporation system at 200 frames per second to track whole body movement of 8 LPGA players to determine the effectiveness of partial swings for player rehabilitation.

Wallace et al. [18] used a five camera Motion Analysis system to track whole body (14 segment) movement of the player. They looked at 9 players hitting shots with drivers of 4 different lengths. Similar methods were used by Egret et al. [19], who used a five-camera Vicon system at 50 frames per second to track whole body kinematics of 7 skilled players swinging three different clubs.

All of the studies mentioned above studied relatively small numbers of subjects. This is not surprising given the challenges of motion capture. Often studies required hand digitization, or, at best, laborious attention paid to the marker data to identify markers and tracks that appear and disappear from view of the cameras. With improving ease of use and lowering costs of commercially available motion capture systems, studies that used more cameras to track more body segments of more players is becoming practical. Nesbit [20] used a Motion Analysis Corporation system tracking 23 markers running at 180 frames per second to collect whole body swing data on 84 players of various skill levels. Joint angle data calculated from this motion data was used to kinematically drive simulation models to investigate the dynamics of the swings of a variety of players. Myers et al. [21] used an eight-camera Peak Motus system (currently available as the Vicon Motus system) running at 200 frames per second to study the hips and torso movement of 100 players. They used a relatively simple marker set, with three markers on the pelvis, three on the upper torso (specifically, the back of the neck at the level of the C7 vertebra and the left and right acromion processes), as well as the elbows. Two additional markers were attached to the shaft of the club to identify swing phase. In this study, the researchers found a significant difference in the amount of shoulder turn relative to hip turn between players grouped by ball speed.

A few recent studies have focused on some of the challenges faced when collecting motion capture data on the golf swing. Betzler et al. [22] used a comprehensive experimental protocol, featuring a 12 camera Vicon system running at 250 frames per second to track 48 markers on the body (and two markers on the club), but he looked

at only 2 players. This paper, which predominately was about the methods, noted some of the challenges faced when doing motion capture on golf. The authors noted a need for a high capture rate to identify velocity peaks. Marker occlusions were a challenge, as was secure club-marker attachment.

Wheat et al. [23] dug deeper into some of the details of motion capture in golf. They studied different ways in which the orientation of the upper torso can be represented, using different markers. They used an eight-camera Motion Analysis Corporation system to track 8 markers at 300 frames per second. They examined 10 players taking 8 drives each. They compared the alignment of the upper torso represented by markers attached to the torso, as opposed to markers attached to the shoulders (acromion processes), and showed that they are quite different. This is important if one wishes to use the motion capture data to try to determine loading in the spine, or if you are trying to compare 'torso' rotations between studies that use different methods. They did not discuss which method may be preferred for golf teaching or coaching.

Like the comprehensive study of Nesbit [20], several studies that have included some motion capture of the golf swing have been done not as observational studies, but rather to collect data to drive or validate simulation models of the golf swing. Brylawski [24] used motion capture of the golf club of a single subject to validate a simulation model. Miura and Naruo [25] use two-camera motion capture of the club only in the swings of players of varying skill-level in an attempt to validate simulations. Iwatsubo et al. [26] use motion capture of the golf swing of a robot to validate a model of shaft torsion.

NON-OPTICAL METHODS IN THE SCIENTIFIC LITERATURE

Much of the scientific literature describing the use of motion capture in golf is based on optical methods. However, other measurement modalities have been used for researching the golf swing.

Cheetham et al. [27] used a magnetic tracking system to study the swings of 10 highly skilled and 9 less skilled players. They examined the X-Factor, and specifically the increase in X-Factor at the beginning of the downswing. Neal et al. [28] describe the use of a magnetic tracking system to study the swings of 25 skilled players and discuss the body segment sequencing. Four sensors are used: sacrum, thoracic spine, left upper arm and left hand.

Use of goniometers or instrumented linkages has also been reported in the literature. McTeigue et al. [29] used an instrumented linkage to track the movement of the upper torso relative to the pelvis in 51 PGA players, 46 Senior PGA players and 34 amateur players. This study is particularly noteworthy as it documents the quantification of the concept of X-factor: the rotation of the shoulders relative to the hips, often viewed as an important aspect of the golf swing that is expected to be a distinguishing difference between skilled and unskilled players. It is also a noteworthy study as it included measurements of relatively large numbers of players, particularly elite players. A similar experimental method was used by Lindsay and Horton [30] to compare the kinematics of the lower back of back pain sufferers and non-sufferers.

A relatively unique study is that of Teu et al. [31], who used electrogoniometers on the left shoulder, elbow and wrist of to study the kinematics of the upper extremity of

2 players.

Ultrasonic motion tracking uses an array of sound sources and microphones to track their relative positions. This method is restricted in range, and line-of-sight must be maintained for accurate tracking. However, the method has been applied to the putting stroke. Marquardt [32] describes the use of the SAM PuttLab to quantify the putting stroke of 99 PGA players. Sampling rate is 210 hz. This technology is commercially available and is marketed by Science&Motion GmbH (Munich, Germany).

Inertial tracking systems have not been used extensively in research literature. Swider et al. [33] mentioned the use of miniature accelerometers to measure the movement of the golf club in a robot-simulated swing. Papers by Lee et al. [34] and King et al. [35] describe the development of a method to measure the golf swing using a club instrumented with inertial sensors. However, these papers described only the methods for measurement, but did not describe the application of the method to understand the golf swing, or for teaching or coaching.

COMMERCIAL APPLICATIONS OF MOTION CAPTURE IN GOLF

NON-OPTICAL SYSTEMS

Inertial Systems

Inertial systems, using accelerometers and rate gyros for measurement of the movement of the golf club and the player, have become available commercially. Accelerometers in their simplest form are small masses suspended on beams that have been instrumented to measure load or deflection in the beams. Once calibrated, the accelerations of the body to which the supporting beam are mounted can be determined. Early forms of accelerometers were relatively large and delicate devices, so their application was limited to research laboratories. Micro-electro-mechanical systems (MEMS) accelerometers have been developed that operate by essentially the same principles, but the beam/mass structure is etched onto a microchip, making the devices small and robust. MEMS rate gyros that measure angular velocity have also been developed. The widespread use of MEMS accelerometers and rate gyros for applications such as crash sensors for controlling supplemental restraint (air-bag) deployment on automobiles has led to low cost, compact systems for measuring accelerations and angular rates.

Theoretically, if one measures accelerations and angular rates of a body in three non-parallel dimensions, one can reconstruct the time-history of the position and orientation of the body. To do this in practice, one must make either precise measurements of initial positions and orientations, or one must be able to make some accurate assumptions about initial (or final) positions and orientations. Additionally, some relatively sophisticated signal processing must be done to reconstruct the movement of the bodies. Very slight errors in the calculated orientation of the devices will lead to distortions in position and orientation over time. If the movement is relatively well defined with key features that can be expected (such as, in the golf swing, a stationary beginning and end) then these features can be used to 'tidy up' the reconstructed movement. Also, if the bodies are known to be connected in some way (e.g., the upper torso being attached to the lower torso by the spine) then assumptions

can be used to constrain the reconstructed movement of one body relative to another.

Inertial systems have some specific advantages over other motion capture methods. They are wireless, and are not interfered with by any environmental factors, such as sunlight (like optical systems) or metal (magnetic systems). Specific disadvantages are their precision in position reconstruction, and their accuracy when the body is rotating at high speeds (e.g., the golf club). The software that reconstructs the movement of the player or the club from the inertial sensors must use an assortment of assumptions to overcome the challenges of system initialization. As a consequence, the resulting movements can be distorted either because of the limitations of the inertial tracking or the assumptions that have been made in an attempt to overcome these limitations.

Such methods have presumably been used in several inertial motion measurement systems that are commercially available. Systems such as the IGS-190 system marketed by Animazoo Ltd UK (Brighton, UK) (<http://www.animazoo.com>), and the Movens system marketed by Xsens Technologies BV (Enschede, Netherlands) (<http://www.xsens.com>) are whole-body motion capture suits, marketed typically for animation motion capture applications. In addition to general-purpose inertial motion capture systems like these, there are golf-specific inertial motion capture systems. These systems take advantage of the known or expected parameters of a golf swing to aid in the reconstruction of the movement. Additionally, they include in their software an assortment of tools or features that are specifically designed for golf instruction. Motus Corporation (Boston, MA) (<http://www.iclub.net>) market two products based on this technology. The first, iClub, is a device that attaches to the butt end of any golf club. This device measures the movement of the club through the swing and then communicates wirelessly to a computer, which then displays an animation of the movement of the club and presents an assortment of measurements of the swing, applicable to golf instruction. Another product that they market is the Body Motion System which uses similar technology to track the movement of the upper torso and the lower torso. A similar product, the K-Vest (<http://www.k-vest.com>) is marketed by K-Motion Interactive Inc. (Bedford, NH) (<http://www.k-motioninc.com>). This is also a wireless inertial system that tracks the upper torso and lower torso as well as the lead hand and is marketed specifically for golf instruction.

Magnetic Systems

Magnetic systems are also used to measure the golf swing. Commercially available general purpose magnetic tracking hardware, such as the Liberty system, marketed by Polhemus (Colchester, VT) (<http://www.polhemus.com>) has been used for examining the golf swing. The technology uses a transmitter that generates a magnetic field and one (or several) sensors that measure the generated magnetic field. The position and orientation of each of the sensors can be determined. So, when attached to a body of interest (such as a limb segment or a golf club), only a single sensor is needed to determine the complete rigid body position and orientation. Systems are available that can track up to 16 sensors simultaneously, at capture rates of up to 240 hz, making this a reasonably attractive choice for tracking movements like the golf swing.

Magnetic systems have some disadvantages. Most magnetic systems require the

sensors to be wired. Wireless systems do exist, such as the Liberty Latus system marketed by Polhemus. However, the wireless sensors are more massive, and tracking precision is reduced. In golf, the player is stationary so wired markers can be accommodated. Metal objects in or near the capture area can also interfere with the use of magnetic systems. Again, however, in golf, these limitations can be avoided.

Magnetic systems also exhibit some specific advantages. Line-of-sight between sensor and receiver/transmitter does not need to be maintained, which is a big advantage when tracking the golf swing with large rotations and translations of limb segments. Additionally, ambient light does not interfere with the capture (as it can for optical methods) so that magnetic systems can be used outside in direct sunlight. Magnetic systems do not require complicated calibration procedures by the end user. Magnetic systems can be used in real-time relatively easily, so they can be used for biofeedback applications. Also, magnetic systems are moderately priced, making them reasonably affordable for golf teaching and research applications.

A few companies have used magnetic tracking hardware and developed their own software to make golf-specific systems. Golf Biodynamics Inc (Miami, FL) (<http://www.golfbiodynamics.com>) uses a magnetic tracking system and software to present and analyze golf-specific results (Rob Neal, personal communication). This system is based on the AIM-3D Golf system marketed by Advanced Motion Measurement LLC (Phoenix, AZ) (<http://www.advancedmotionmeasurement.com>). These systems have between 4 and 6 sensors on body segments from the pelvis through the hands. They measure relative body segment movements through different phases of the golf swing and compare them to normative data based on large numbers of swings measured previously on the system. The Golf Biodynamics software includes an expert system that can draw attention to aspects of the swing that are out of the ordinary and can provide insight into any physical limitations that the player may have that are influencing his or her swing. Additionally, the system can be used in real-time to provide biofeedback: giving immediate feedback to the player when movements are outside of desired target ranges. Golf Biodynamics' use of the motion tracking system is principally focused on assessing the physical capabilities or limitations of the player. This information would ideally best be used by a physiotherapist or physical trainer to aid in preparing the player to play golf.

GolfTec (Centennial, CO) (<http://www.golftec.com>) is another company that uses magnetic tracking for motion capture of the golf swing. GolfTec has numerous teaching centers throughout the United States that feature their proprietary magnetic tracking system based on hardware manufactured by Polhemus. The movement of the players' hips and upper torso are measured by attaching magnetic markers to the body using a small harness. This motion capture data can be displayed synchronously with video of the swing to aid in the interpretation of the results. The GolfTec system also features biofeedback using audio tones to inform the player of desired or undesired movements. GolfTec has developed a set of desirable ranges of movement based on tour player swings, and they accumulate an archive of all of their player data. GolfTec's use of the system focuses on golf instruction and the intended use is to compliment or supplement instruction from a teaching professional.

OPTICAL SYSTEMS

Optical motion capture systems are also in use for commercial golf applications. Optical motion capture systems use cameras to track either active markers (that emit light) or passive markers (that reflect light), or are markerless.

Markerless Optical Systems

Video, and high-speed video using one or two camera views have been used to record and observe the golf swing for many years. An assortment of tools for managing and manipulating video for qualitative analysis of sport, and specifically golf exist and include Dartfish (Fribourg, Switzerland; <http://www.dartfish.com>), and V1 (Interactive Frontiers, Plymouth, Michigan; <http://www.v1golf.com>). These video systems can be very useful for examining qualitative aspects of the golf swing, but are difficult to use in a quantitative way. Digitization (quantification of points of interest) by hand can be done, but it is laborious, and the precision of the quantification of the movement depends upon the quality of the video and the skill of the operator. Services are available that will provide quantitative assessment of the golf swing based on video, such as zenoLINK (Welsh-e Technologies, Endicott, New York; <http://www.welch-e.com>).

Markerless motion capture, where the movement of the player is quantified automatically without markers being attached to the player's body or club is only just now becoming available. Using a system featuring multiple cameras and a contrasting background, Organic Motion (New York, New York; <http://www.organicmotion.com>) started in 2007 to market a system that does automated, quantitative markerless motion capture. 4D View Solutions (Grenoble, France; <http://www.4dviews.com>) markets a related technology that generates three-dimensional images from multiple camera views. These systems shows potential for golf swing assessment and coaching, but this author is not aware of anyone yet using this technology in golf.

Active Optical Systems

By using markers attached to the player and/or the golf club, optical systems can more easily be used to quantify the movement during the golf swing. Active marker systems, such as the Optotrak systems marketed by NDI (Waterloo, Ontario, Canada; <http://www.ndigital.com/research>) or the Phase Space system marketed by Phase Space (San Leandro, California; <http://www.phasespace.com/productsMain.html>) use LED lights as markers and cameras or optical detectors to observe these light sources. These systems typically require the markers to be wired, encumbering the player. Additionally, often these active markers have limited angle of emitting of light from the markers impairing their visibility. An advantage of active systems is that the markers can be identified explicitly by the timing or encoding of the light that they emit. However, the increasingly sophisticated tracking capabilities of passive optical systems seem to be reducing this specific advantage of active systems.

Passive Optical Systems

Passive marker optical motion-capture systems are used widely in the fields of motion capture for entertainment (video game and movie animation), medical and sport biomechanics research, gait analysis and industrial applications. The markers

are simply reflective spheres (or stickers) without wires. This means that there is a minimum of interference in the movement of the athlete, actor, or subject of study. Such systems are marketed by several manufacturers including Vicon (Oxford, UK; <http://www.vicon.com>), Motion Analysis Corporation (Santa Rosa, California; <http://www.motionanalysis.com>), and Qualisys (Gothenburg, Sweden; <http://www.qualisys.com>). The systems marketed by these companies are general-purpose motion capture hardware and software that the user can tailor to whatever movements or activities are to be measured. Motion Reality Inc. (Marietta, Georgia; <http://www.motionrealityinc.com>) who has a long history of motion capture system development for research and entertainment applications, have collaborated with TaylorMade-adidas Golf (Carlsbad, California; <http://www.taylormadegolf.com>) to develop a golf-specific motion capture system. The systems used by TaylorMade-adidas Golf are called Motion Analysis Technology by TaylorMade (MATT) and are used principally for club fitting. Much the same technology is used in the Motion Reality Golf system, which is marketed principally for golf instruction. This author participated in the development and use of these systems, so much of the following discussion will focus specifically on them.

Passive marker systems typically use spherical reflective markers and cameras paired with lights. The lights are usually co-located with the cameras as the markers are retro-reflective (reflecting light back in the direction from which it came). In this way, the reflective markers can have quite a high contrast in the view of the cameras. Even so, optical systems typically cannot be used in environments with sunlight, and highly reflective surfaces (such as steel golf club shafts) can cause problems in marker identification and tracking. This means that motion capture is usually limited to indoor applications, and the capture space (and golf equipment) need to be designed or modified to be “friendly” for motion capture. Some MATT facilities have been made where the motion capture room has a large door that opens up onto a driving range, so motion capture of the swing can be made while balls are hit out onto the range. This has been made to work when sunlight is not coming through the door directly into the capture area, with some careful modifications to the system to account for the sunlit space.

CAMERAS AND CAPTURE RATE

For high-speed movements like the golf swing, the cameras used for motion capture tend to be high-speed cameras (faster than 60 frames per second) and tend to be high-resolution cameras for improved precision. It has been pointed out previously in the literature that higher speed cameras are desirable when doing motion capture of the golf swing [22]. The objective of the golf swing is to propel the ball a suitable distance in a suitable direction. The velocity, position and orientation of the clubhead as it impacts the ball are critical for achieving this objective. Ideally, then, if the purpose of the motion capture of the golf swing is to assess performance measures, high precision measurements of clubhead velocity, position and orientation at impact are desirable. During the swing of a driver, the clubhead can achieve speeds of more than 50 m/s. Therefore, if the capture rate is 200 frames per second, the clubhead can be traveling 0.25 m from one frame to the next. That is, the last frame before impact can be as far away from the ball as 0.25m. This can dramatically impair ones ability

to precisely determine clubhead position and orientation at impact. Therefore, the faster the frame rate of the cameras, the better the precision of the measurement of the clubhead at impact. Additionally, even with high frame rates, great care and attention must be paid when extrapolating the movement in order to most accurately predict impact conditions.

Three-dimensional motion capture can theoretically be accomplished by a pair of cameras. However, to ensure visibility of multiple markers on multiple body parts and to avoid marker occlusion throughout the movement, multiple cameras are required for practical motion capture of the golf swing. Depending upon how tolerable temporary marker occlusion is (which depends upon the robustness of the marker tracking and motion reconstruction methods as well as the accuracy and precision required), as few as four cameras may suffice for full body motion capture. However, typically six or more are used. Again, theoretically, camera placement can be arbitrary. However, in practice, some care and attention must be paid to camera placement to maximize marker visibility throughout the golf swing. Additionally, practical considerations (e.g., ensuring that cameras are not likely to be hit by stray shots) will constrain camera placement. A simple and practical arrangement of cameras would have equal numbers of cameras spaced evenly behind and in front of the player when the player is in the address position. Placing some cameras near the floor and some cameras near the ceiling would improve the relative angular displacements of the cameras which can theoretically improve marker tracking. But again, practical considerations may counter this. Cameras near the floor in front of the player can be a distraction to the player. Additionally, if all of the cameras are at roughly the same level (up high, near the ceiling), they can be pointed in such a way that cameras are either not in the field of view of one another, or they are near the perimeter of the field of view of one another. This eliminates the challenge caused by the lights of other cameras appearing to be markers. So, perhaps the most practical arrangement of cameras for motion capture in golf is a horse-shoe shaped arrangement, up high around the perimeter of the hitting area.

While performing the golf swing, the player typically stands in place. Therefore, the capture volume does not need to be very large. If the focus of the measurement of the golf swing is on the player and precise measurements of the movement of the club throughout the swing are not required, then the required field of view can be quite small. The same is true if only putting is to be measured. However, for capturing the full golf swing, one must not forget that the arc that the clubhead passes through during the swing can be quite large. When selecting lenses, positioning and aiming cameras, the entire arc of the swing must be taken into consideration. Also, if the same camera setup is to be used for both left and right handed players, then both must be considered. The narrower the view angle on the lenses and the closer the cameras are to the player, the better the precision of the marker reconstruction. At the same time, one must not miss parts of the movement, making the task of optimal camera placement delicate and tedious.

PLAYER AND CLUB MARKERS

Selecting a marker set is a very important step in any motion capture activity. The golf swing is no exception. The marker set used must:

- Provide sufficient marker visibility, minimizing marker occlusions by limbs throughout the golf swing
- Not interfere with the movement of the player during his or her golf swing
- Be sufficient to reconstruct the movement of the player to the level of accuracy and precision required

In addition to these requirements, there are additional aspects of the marker set that should be considered to simplify the data collection process. The marker set should:

- Be comfortable to the player
- Be easy to apply (and remove) in a reasonable amount of time
- Be easy to apply with a reasonable level of precision

These requirements and desired aspects of the marker set can be difficult to balance. Again, depending upon the application (research, teaching, coaching or club fitting) there may be an assortment of suitable compromises.

The above comments are true of almost any motion capture activity. Marker placement for capturing the golf swing poses some specific challenges. For example, tracking of the arms can be very difficult because of very large angular excursions in adduction/abduction, flexion/extension and internal/external rotation at the shoulder. Also, the movement of the arms across the chest of the player makes placement of markers on the front of the torso very troublesome. The rapid movements of the hands, as well as the large angular excursions of the rotations of the hands and the grip of the club, all make precise tracking the movement of the arms, shoulders and upper torso of the player difficult.

To absolutely and unambiguously reconstruct the position and orientation of a rigid body, the position of three markers rigidly attached to that body must be identified. To represent the position and orientation of all player limb segments and the golf club would therefore require a very large number of markers. Attaching so many markers to a player is usually not practical. Additionally, it is often not possible to rigidly attach markers to body segments, which themselves are often not well described as rigid bodies. Therefore, most motion capture methods will make compromises in the markers that are used. If assumptions are made about how joints between the limb segments constrain the relative movements between two limb segments, then the number of markers needed to reconstruct the position and orientation of those two limb segments is reduced. The suitability of the assumed set of constraints depends upon what is being investigated. As far as this author is aware, no standardized marker set for the tracking of the golf swing has been adopted. Therefore, it is currently still up to the individual investigators to select a marker set and a set of kinematic constraints that suit their purpose.

For medical or biomechanical research studies, often markers are placed directly on the skin of the subject (Nesbit [20], for example) at anatomical landmarks. Often large numbers of markers are used, to achieve the required precision of the motion tracking. However, the application of these markers can be time consuming, are intrusive to the subject and require considerable expertise on the part of the

experimenter. For motion capture for animation, tight clothing with markers attached, or Velcro integrated into the clothing for easy marker attachment is often used. This makes marker attachment much faster, but can still be somewhat intrusive. The MATT system uses a smaller number of markers easily applied over the top of typical golf clothing on neoprene and Velcro straps, a light vest, and a baseball cap. Several markers are located on the top of the shoulder and on the upper back applied to the player on a lightweight vest. Four markers are attached around the hips of the player on a neoprene and Velcro belt, while neoprene and Velcro straps attach marker at the knees, elbows and wrists. Slip-covers are put on over each shoe, with three markers attached to each foot while a baseball cap with three markers is worn. Standardized test clubs with markers already attached are used.

Since many of the markers are applied in locations that are convenient, rather than at anatomical landmarks, a scaling process is employed. Prior to the capture of the golf swings, a few extra markers are temporarily applied, the player stands in the capture volume in a specific posture, and the position of all of the markers is captured by the cameras. Such a neutral trial, or static trial, or scaling trial is a relatively common procedure in motion capture. The temporary markers are used to identify the position of joints relative to the markers that will remain on during the motion capture. For the MATT system, four temporary markers are used: one on each greater trochanter, and one on the anterior aspect of the shoulder, roughly on an anterior projection of the shoulder joint center. The player stands upright, facing away from the hitting direction, with elbows straight, and arms abducted from the sided roughly 45 degrees.

This marker set used by the MATT system can be applied in just a few minutes and requires only a little expertise from the operator to apply. The player wears the markers overtop of their own clothes, making it minimally intrusive. A carefully selected kinematic model of the player and a sophisticated tracking and movement reconstruction algorithm make best use of this sparse marker set to capture the movement. The absolute precision of the tracking of the various limb segments of the player is less than that which might be required for biomechanical studies of kinematics of individual joints. However, the essential movements of the player are captured with sufficient precision for comparing the movements of two players, or of one player hitting different clubs, or before or after some swing change. Additionally, the marker set on the clubs are firmly attached and precisely measured to give the best precision possible for tracking the club's movement.

Even considering the golf club in isolation, placement and attachment of the markers is not a simple task. Aside from putters, the golf club should not be treated as a rigid body as the shaft can flex considerably during the golf swing. If one wishes to precisely track the movement of the club, one must track the clubhead and the grip independently. To track them independently, one typically would require three markers rigidly fixed to the grip and three markers rigidly fixed to the clubhead. These three markers must not be collinear. If they are near collinear, then small errors in marker position identification can lead to large errors in body orientation determination. To avoid collinearity and to improve marker visibility from cameras, markers near the grip may best be attached using stems or rods, offsetting the markers from the shaft. At the clubhead, avoiding collinearity of the markers may not be as

challenging. However, markers are still best offset from the clubhead using stems to ensure good marker visibility. When the clubhead contacts the ball, the accelerations that the clubhead are subjected to are great. Therefore, marker attachment can be very challenging. In our experience, very light markers are required to minimize the forces that result from the rapid acceleration. Even with very light markers, strong bonding agents were still often not sufficient to prevent markers coming loose. For the MATT system, markers on the clubhead are attached to either steel (for putters and irons) or titanium (for drivers) pegs welded onto the clubheads. Even these welded pegs cannot withstand contact with the ball, however. So markers were placed in locations that were less likely to come into contact with the golf ball during a mishit.

MARKER TRACKING

Optical motion capture systems reconstruct marker positions from multiple camera views using the direct linear transform (DLT) method. Through the use of sophisticated calibration algorithms, the DLT with extra terms can account for imperfections in camera geometries, reducing the need for expensive precisely manufactured cameras. Historically, the calibration procedure was time consuming and required very precisely measured arrays of markers throughout the capture volume. However, most commercially available motion capture systems now use calibration algorithms that minimize the need for expensive equipment and make the calibration procedure relatively quick and easy.

The DLT algorithm can determine the position of a marker in space provided that it is viewed in more than one camera. If there are multiple markers in the field of view, then an additional challenge is in identifying which marker is which. Modern motion capture systems usually have tracking algorithms that aid in identifying which marker is which. The tracking algorithm typically is given information ahead of time about the number of markers that are expected and their position relative to one another. Once the markers are in the field of view, it is also typically assumed by tracking algorithms that the markers will move smoothly and continuously, so marker identification from one time step to the next is aided by prior knowledge of the probable position of the marker. When markers disappear from view or reappear due to occlusion by body parts, the capabilities of these tracking algorithms can be strained.

Most commercially available motion capture systems tend to have robust tracking algorithms that can overcome challenges caused by marker occlusion. One consideration that is specific to golf is caused by the clubhead impacting the ball. Many tracking algorithms essentially assume smooth continuous motion from the markers. The clubhead decelerates very abruptly when contact is made with the ball and this can cause problems for some tracking algorithms. Furthermore, if the clubhead strikes the ball off-center, in addition to an abrupt deceleration of the clubhead, there is an abrupt rotation of the clubhead. That can lead the tracking algorithm to mistake the markers on the clubhead for one-another. Since the MATT system was designed specifically for tracking the golf swing, provisions are made in the tracking algorithm to account for this abrupt change in clubhead speed and orientation at impact.

MOTION RECONSTRUCTION

Once the positions of the markers on the player and the club are identified, the movement of the entire player and the club must be reconstructed. A set of assumptions are made to construct a kinematic model of the player and club. This kinematic model is typically a set of rigid bodies representing limb segments connected by an assortment of joints that roughly represent anatomical joints. Since the number of markers attached to each limb segment is often smaller than what is required to reconstruct the position and orientation of each segment, typically the position and orientation of all body segments must be fit at once, while applying the assumed joint constraints. This step of the motion reconstruction is typically done by software that comes with the motion tracking system, such as BodyBuilder (Vicon), Skeleton Builder (Motion Analysis Corp.), or Visual3D (Qualysis). Once the model of the player is defined, and the position of the markers relative to that model are defined, the software can reconstruct the position and orientation of all of the body segments and all of the joint angles can be calculated.

This is a very important aspect of any motion capture study. The kinematic model that is selected to represent the movement of the player can influence the results. Additionally, the selection of the marker set used cannot be separated from the selection of the kinematic model that is used, as they depend extensively on one-another. The marker set used and the kinematic model selected will depend upon the aspects of the golf swing that are under investigation. A study in the literature investigated such implications on the tracking of the upper torso or shoulders during the golf swing [23].

For example, for the full swing, the MATT system uses a compromise in kinematic model and marker set complexity at the hands of the player. The club is tracked very carefully using a set of three markers on the clubhead and three markers on the grip. It can be difficult to attach markers to the hands of the player in a way that does not interfere with the player's movement or grip of the club. Also, if a large number of markers are applied to the hands of the player (as well as the grip of the club), it can be difficult for even the best tracking algorithms to identify the various markers. Therefore a compromise is made: a single marker is attached to each of the player's wrists, no markers are applied to the hands, and the hands are assumed to stay rigidly attached to the grip of the club. In this way, the precision with which the movement of the wrists and hands are measured is compromised somewhat, and the details of the way in which the player has gripped the club cannot be observed using the data collected by the MATT system. If one wished to study precisely the movement of the hands and wrists, perhaps for the purposes of understanding hand or wrist injuries, such a selection of marker set and kinematic model may not be suitable. However, the precision of the tracking of the movement of the club is not compromised, and there is no obstruction or interference with the player's grip and they can wear their own glove if they choose. So for the purposes of club fitting, where the precise tracking of the club is required and the comfort of the player is important, this is a suitable compromise.

MOTION PLAYBACK AND PRESENTATION OF RESULTS

Once the kinematics of the player have been calculated, additional software is used

to either animate the movement, or calculate specific results of interest, or both. What is required at this stage depends considerably on the purpose of the motion capture. Many software tools are available that can take the measured movement and generate an animated reproduction of the movement. This may be a simple stick figure, or may include some geometry applied to the kinematic model to better visualize the movement. Most modern motion capture systems can integrate the animation of the movement into the software tools that perform the tracking and motion reconstruction. Many systems can do this tracking, reconstruction and animation in real time, presenting an animation of the movement almost simultaneously with the movement being measured. Also, presumably, if the motion capture is being done for the purposes of a research study, the measurements of interest will be extracted from the reconstructed kinematic data and can be plotted or presented in real time, or immediately after the capture is completed. An assortment of tools for results extraction and presentation are available to the skilled and experienced user of general motion capture systems. Just exactly what results are extracted and how they are presented depend upon the application.

For the purposes of teaching or coaching, the playback of the animation may be very useful, and may be the desired outcome of the motion capture activity. The playback of the animation can serve a purpose similar to the playback of a video of a player's swing so he or she can see exactly how they move. However, a very important advantage of the motion capture data over the playback of video is that the movement can be measured and annotated automatically in countless ways. For example, the MATT system:

- Automatically identifies key events of the movement including: address (stationary beginning of the swing), top of the backswing (minimum speed of the club at the end of the backswing), impact (when the club makes contact with the ball) and finish (stationary, or minimum speed of the clubhead at the end of the follow-through), and provides the tools to go immediately to these key frames.
- Permits the viewing of the swing from any direction.
- Plays back the swing with a frame rate higher than typical high-speed video without any blurring for very slow motion, or still-frame viewing.
- Can highlight movement of bodies of interest (such as the hips, shoulders, grip, clubhead, etc.) by adding lines to improve the visualization of the movement and quantifying the orientation of these lines relative to the current view.
- Can display curves or surfaces followed by bodies (the clubhead or shaft) throughout the swing to help visualize time-varying aspects of the movement.
- Can display swings side by side or overlaid to compare two swings.
- Can calculate and display individual measures of interest, such as clubhead speed, clubhead path through impact, face angle and loft at impact.
- Can report durations and/or timing of swing events.
- Can turn off or on the display of the club or the player to draw attention to particular aspects of the swing.
- Can augment the display with various reference lines to help visualize aspects of the movement.

This is a partial list. The various ways in which the playback and visualization of motion capture data of the golf swing can be augmented to aid in golf instruction is limited only by the imagination of the teacher or coach, and his or her programming skills with their motion capture system and/or software package that they are using. It is here perhaps that a motion capture system developed specifically for golf exhibits the greatest advantage over a general-purpose motion capture system. The playback and augmentation of the swing, as well as the extraction of results relevant for golf is simplified and automated in a system developed specifically for golf.

The use of real-time playback of the movement can be interesting also. The golf swing is so rapid, and typically requires the player to focus on the ball, so it is not practical for a player to watch a monitor displaying his own swing in real-time while swinging full speed. However, if a target position is displayed on the screen, such as the address position of a player that the student wishes to emulate, and the movement of the player is displayed in real-time overlaid on the target position, the player can position themselves to match the target position. This is a relatively unique feature of motion capture that may have interesting application in golf instruction.

CLUB FITTING AND EQUIPMENT DESIGN

Motion capture can be used for the quantification of various measures of the golf swing beyond those that might be immediately helpful or interesting for golf coaching or instruction. The MATT system was developed principally as a club-fitting tool, rather than a tool for golf instruction or coaching. Traditionally, club fitting has consisted largely of trial and error. Some measurements were made to determine a few club specifications, such as the length and lie of irons. However, for determining the model or style of a particular club, or even the loft of a driver, typically a player would take several shots with several different clubs and decide which clubs he or she liked and performed best with. With the MATT system, this process is modified. Several shots are taken with a standardized club. Based on numerous measures from these swings, as well as the answers to a short questionnaire, a recommendation is made for the clubs that would best suit the player's swing.

For the purposes of club fitting, there is a data collection protocol that is followed. The player will complete a short questionnaire that has questions about the player's typical performance on the golf course and some questions about any preferences in club properties. The player ensures that he or she is warmed up to hit shots. The markers are applied and the player is scaled. Then, 6 shots are made with a 6 iron, 6 shots are made with a driver and, at facilities that have high nets that can receive wedge shots, 6 shots are made with a sand wedge. Typically, the playback of the animation of the golf swing is not shown to the player during this protocol, as often upon seeing the animation of their swing, players can become aware of some aspect of their swing that they immediately try to modify, thereby distorting this data collection process. Once the swings are collected, the system automatically extracts the measurements from the swings, and, together with the information collected during the questionnaire, uses this information in a proprietary algorithm to recommend a set of clubs that will best suit the player's swing. This recommendation includes both the model of club as well as the specifications for that model, such as

shaft flex, driver loft and iron lie. If any of the standardized clubs are not included in the protocol, then the relevant club recommendations will not be made. For example, if the player does not hit wedges, only driver, fairway and iron recommendations will be made, and no wedge recommendations will be made.

To compliment the motion capture data, the MATT system also integrates measurements made using a launch monitor. The launch monitor uses different optical technology to observe the ball shortly after it has been struck. Typically, the ball speed, launch angle, backspin rate, deviation angle and sidespin rate are measured by the launch monitor, and these data are shared with the MATT system. This launch monitor data is combined with the questionnaire and swing measurement data when the club recommendation is made.

The MATT system can also be used to aid in fitting putters. With putters, however, the relationship between swing measurements and a preferred putter is not as clear as it is for the other clubs in the bag. Putter preference is much more based on aesthetics and other subjective aspects of performance. Therefore, the putter recommendation is not as precise as the other club recommendations. The putter recommendation is currently limited to a few aspects of putter style that the player may prefer, but does not specify a putter model.

Once the player has completed the fitting protocol, the system operator (who is often a club fitter and/or a teaching professional) often shows the player his or her swing. The animations, augmented visualization of the swing and the large amount of data of the swings collected can be quite compelling, and often lead to a discussion about swing flaws, swing style, ways to improve performance, and so on.

In addition to using the data for an individual to recommend products for that individual, a large data set is now available for examining the swing characteristics of a very large population of players. As of the writing of this article, there are 20 MATT systems in various facilities around the world, most of which are used principally for club fitting. The first of these systems was installed in 2002. So far, hundreds of thousands of swings have been collected on tens of thousands of different players. Much of these data were collected using the protocol outlined above. All of this data set, including motions, extracted results and the answers provided in the questionnaire is archived in a central location. This data set can be used to better design products that best suit either the population of all players, or to design products that suit sub-populations of players with specific swing characteristics.

MOTION CAPTURE FOR GOLF INSTRUCTION AND COACHING

The numerous ways in which the playback of the golf swing can be augmented as listed above make motion capture a powerful tool for golf instruction. Studies have looked at the influence of the use of video on the effectiveness of golf instruction [36, 37]. These results suggest that, the use of video improves the effectiveness of golf instruction over the long term but not the short term. Similar studies have not been done on the effectiveness of motion capture, so motion capture has not been shown conclusively to improve the rate of improvement of players. However, if the excitement or enthusiasm of many of the teachers, coaches, students and players is any indication, motion capture is likely to make an impact in golf instruction.

For the beginning player, golf instruction can be very confusing. The jargon in golf for describing positions, orientations and movements of the club and body parts is extensive. Expressions and phrases like “open” (which means something different for the club than for the hips or shoulders), “inside the line”, “out to in path” and “clear the left side” are common and need to be understood to make use of a lot of verbal or written golf instruction. However, with the use of video or animation from motion capture, the student does not need to understand these expressions to compare their own swing to another swing to see how they differ. With motion capture, these movements that can be hard to communicate verbally can even be quantified. The use of real-time capture of the player’s movement with a target movement overlaid can provide the most dramatic demonstration of the elimination of jargon. The instructor or coach does not need to use any words to describe the positions of the player. He or she need only instruct the player to match the target position.

The large set of swing data that has been collected using the MATT systems and other motion capture systems has the potential to be useful for applications in golf instruction and coaching. The MATT data set includes the swings of a few hundred tour professionals. Additionally, one of the questions on the player questionnaire is the player’s handicap. So the swing data can be sorted based on the players’ skill levels. In this way, aspects of the player’s swings that are common amongst all skilled players and are different from unskilled players can be identified. Several past studies have attempted to identify swing differences between skilled and unskilled players [9, 19]. However, of these studies, at most 100 players [26] were examined. Now, we have a data set that includes tens of thousands of players. There is considerably more work to do in this area. With most aspects of the golf swing, however, the variability within a group of skilled players has been found to be greater than the difference between the typical results for skilled and lower-skill players.

This is not the only data set that is large and growing. For example, both Golf Biodynamics and GolfTec archive all of their motion data that they capture during player assessment and instructional sessions. GolfTec has used magnetic motion capture of the torso in golf instruction since 1995 and have estimated the number of lessons taught at over one million. They have measurements of over 150 tour professionals, and their system automates the comparison of an individual’s results to the average of the tour player results. This comparison to the tour averages lies at the heart of their approach to using motion capture technology for aiding golf instruction. A comparison of the average results from these 150 tour players and the averages from 10,000 amateurs (Joe Assell of GolfTec, personal communication) reveals differences. Such examination of these large data sets provides means to identify ways in which any given swing differs from normative data based on average results of the best players. It should be noted, however, that this method assumes that the average tour player result is a movement that any individual should aspire to. Given that there is considerable movement variation among tour professionals, this assumption may or may not be valid.

CONCLUSION

Motion capture is making a slow transition from a tool confined in the laboratory used only by skilled researchers and engineers for research to the golf teaching and

retail location used by instructors, coaches and club-fitters. Improvements in motion capture hardware and software combined with decreasing costs of hardware are facilitating this transition. As these new users are applying this technology to new applications in golf, the advancements and specialization of the technology will likely continue, accelerating this increase in the adoption of these methods. These methods and this technology should not be blindly accepted and used without understanding. Hopefully this paper will have been helpful in providing some of this understanding to the coach, instructor or researcher who is considering the use of, or wished to become more familiar with the application of motion capture in golf.

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