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Development of a golf robot for simulating individual golfer's swings

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Abstract

Golf robots are widely used by manufacturers for equipment testing as players are inconsistent and fatigue. Traditional golf swing robots have a 'standard' swing profile yet every golfer swings a club differently and needs equipment customised for their swing to perform optimally. Therefore, a robot is needed that can replicate different golfers' swings to improve the development of customised equipment. This paper details the evaluation of a golf robot developed to enable biomechanical data measured from a golfer's swing to be used to program the robot to recreate that swing. The angular motions of different golfers were accurately replicated by the robot although differences were observed in the shaft loading between golfers and the corresponding simulation.

Keywords: golf robot; motion analysis; shaft deflection;

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1. Introduction

Golf robots are used widely by manufacturers to test golf equipment as they overcome many of the limitations of player testing. For example, golfer's fatigue and lose interest, but, most notably, the majority of golfers swing a club inconsistently. A well designed robot produces a repeatable swing and so subtle differences in performance can be identified and attributed to the design of the club or ball. The disadvantages of golf robots include the simplification of the swing but, more critically, the inability to vary the swing profile in a controlled, realistic manner. As a result, most equipment testing is carried out using a 'standard' swing profile which is not representative of most golfers.

The majority of golf robots that have been developed are based on a double pendulum model of the golf swing and have three axes of motion, as shown in Figure 1a. The upper lever rotates about a fixed pivot and represents the arm rotating about a 'hub' somewhere between the shoulder blades. The lower lever is the club, which rotates about two axes that represent the wrist joint [1]. The first generation of golf robots typically had a single motor driving the upper lever, with a belt/gear mechanism used to rotate the wrist joint relative to the upper lever. The speed of the swing could be changed but not the swing profile. More recent robots have added independent wrist joints that are

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either free or separately driven but their control systems are usually limited and it is difficult to change the swing profile in a controlled and accurate manner.

This paper presents the development of a golf robot that is capable of simulating different golfers' swings. A new control system has been developed for a commercially available golf robot that enables kinematic data, measured from a golfer, to be used to program the robot to replicate their swing. Swings from several golfers are compared with the equivalent robotic simulations to evaluate the success of the technique. In addition, shaft deflection profiles during the downswing are also compared between golfer and simulation to assess the performance of the robot.

2. Robot Development and Operation

A Miyamae Shot RoboV was modified by AJC Synectics to provide increased functionality and control over the programming of the robot. The aim of the modifications was:

- To improve control of swing profile generation
- To be able to generate swing profiles from kinematic data measured from a golfer
- To be able to assess the accuracy of the swing simulations by comparing feedback data from the motors during the swing with command data

The core structure and mechanics of the RoboV were retained, including the motors for the arm and wrist joints. The control system was completely replaced and the grip rotation motor upgraded from 30 W to 70 W. Robot motion is now controlled from a Trio 4-axis motion controller which is computer programmable over a USB interface. To operate, the robot requires a command file containing 1000 data points that describe the angular rotations of the three axes of motion that are required to produce a specific swing profile. The speed of the swing is then governed by varying the time period over which the swing profile is executed. The motion controller also records feedback data from each motor at a sampling rate of 250 Hz, which can be downloaded and compared against the command data.

Two software programs are used in tandem to program and operate the robot. Profile Designer (PD) is used to generate command files from manually input or imported data to produce a specific swing profile; Robot Manager (RM) is used to configure the robot and execute command files generated in PD. The principle behind PD is to generate 1000 angular data points for each axis of motion by interpolating between a much smaller number of discrete data points (typically between 15 and 40), equally spaced in time throughout the swing. A number of curve fitting algorithms are available to perform this task (linear, Bezier, cubic spline) and the quality of the command file generated has been found to be highly dependant on the curve fitting algorithm used [2]. The quality of fit can be considered in terms of both 'closeness of fit' to the discrete data points and 'smoothness' i.e. a curve free of discontinuities. The cubic spline can also be applied to derivative data and previous studies have concluded that this improved the smoothness of the higher derivatives (acceleration and jerk) but closeness of fit was compromised as a result [2].

The RM software has a number of functions beyond executing the command file generated in PD. The swing plane and height of the robot are adjustable for different clubs. Each axes of motion can be manipulated independently to move the robot into different orientations. Once a command file has been imported, the software can be used to 'jog' through the swing or move to landmark positions such as top of the backswing or impact. Finally, the feedback data describing the actual angular positions achieved during the swing motion can be saved for later evaluation.

3. Robot Evaluation

The efficacy of the golf robot was evaluated by replicating six golfers' swings and comparing data from each simulation with the individual golfer. The first stage in the process was to capture each golfer's kinematic data using a 3D motion analysis system. These were transformed into command files, which were executed by the robot using swing durations that produced clubhead speeds at impact representative of the individual golfers. Feedback data from the motors and shaft deflection measurements were used to evaluate the success of the simulations.

3.1. Kinematic data collection

An active marker, motion analysis system called Codamotion (CODA) was used to measure the motion of multiple marker locations to a high degree of accuracy (±0.05mm) at a capture frequency of 400Hz. Markers were strategically positioned on both the golfer and the club, which enabled a double pendulum model to be recreated in CODA for each golfer's swing. Markers were placed on both shoulder, hip and knee joints, on the shaft of the club and also on an extension piece mounted to the shaft. Virtual markers were then created, by means of fixed geometric relationships between two or more actual marker locations, at sites where actual markers would have been difficult to position. A virtual marker was created at the midpoint between the shoulder markers to define the pivot [3, 4], while another was generated under the golfer's left hand by projecting a line defined by two markers on the shaft, to define the wrist hinge [5]. A link between the virtual markers at the pivot and hinge was used to replicate the upper lever of the double pendulum model, and a link from the wrist hinge to a marker on the shaft produced the lower lever. The angles θ_{arm} and θ_{wrist} were obtained by projecting the angles between the levers onto the XZ' plane (shown in Figure 1b) which was inclined at an angle θ_{swing} to the horizontal. θ_{swing} was determined separately for each golfer using the angle of the shaft to the ground at impact as an approximation of that golfer's individual swing plane angle. Finally, the three markers on the club were used to assign a local co-ordinate system to the club. Euler angles (α,β,γ) were then calculated to determine the orientation of the club, of which, θ_{grip} corresponded with γ.

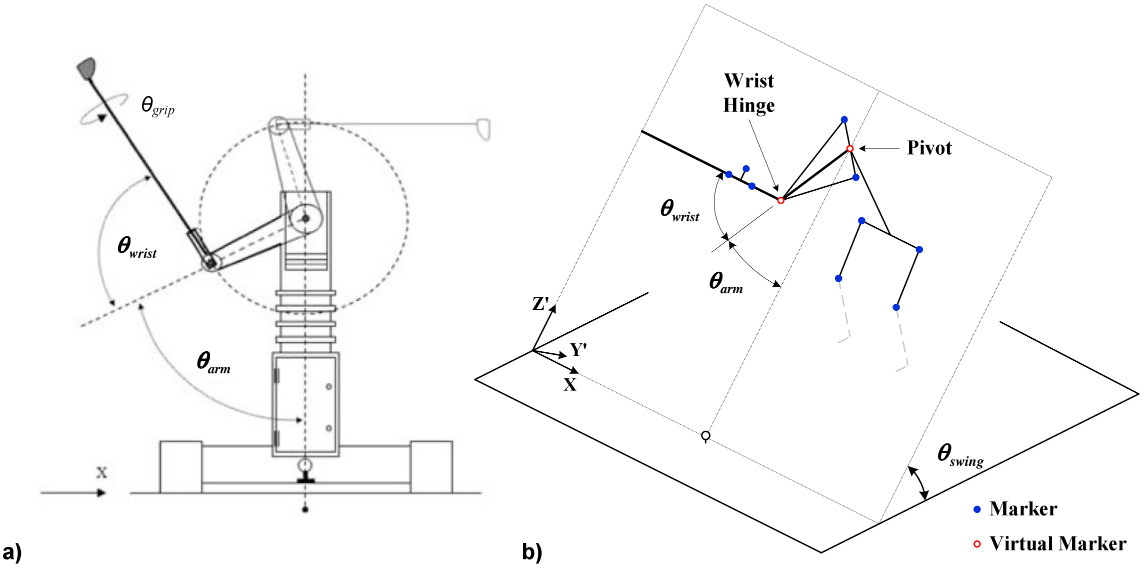

Figure 1 – Golf robot axes of motion (a) and the biomechanical model used to calculate the corresponding angles (b)

Six golfers participated in this study, of which two were female, and four were male. One of the males was a junior golfer, the remainder were all adults. The golfers spanned a wide range of abilities but all had played golf for a number of years. At least five 'good' swings were recorded from each golfer where a 'good' swing was defined as a shot that the golfer was satisfied with, that they had performed well and one which every marker had been captured for at least 95% of the golf swing. Some marker occlusion is inevitable with the complex motion of a golf swing. Interpolated data was used to bridge any gaps in the captured data, providing the gap was brief and the interpolation produced a satisfactory fit when visualised. In addition to the kinematic data, a shaft deflection profile was measured for each golfer using ShaftLab (True Temper). The system uses two strain gauges mounted orthogonally onto a steel-shafted club immediately below the grip to record strain data due to shaft bending in the lead/lag and toe-up/toe-down directions. From these measurements, the software calculates a number of metrics including maximum shaft deflection and clubhead lead and droop at impact.

3.2. Command file generation

A single shot was selected from each golfer, which was considered representative of that person's swing based on the kinematic data. The angular data, θ_{arm} , θ_{wrist} and θ_{grip} , were re-sampled to produce between 30 and 40 discrete data points throughout the swing. A cublic spline curve-fit was then applied to the angular velocity component for each axis of motion to generate 1000 data points and the result integrated to produce the angular displacement data required for the command file. The process of command file generation using different curve fitting algorithms is discussed in further detail by Harper *et al.* [2].

3.3. Evaluation of swing simulations

The performance accuracy of the golf robot was first assessed by comparing the command data with the feedback data from each motor, downloaded from the motion controller after each swing simulation. The angular rotations and velocities are compared for each axis of motion in Figure 2a & 2b respectively, using the simulation of Golfer M2's swing as an example. In addition, the residual data, the angular difference between the feedback and command data, is illustrated in Figure 2c.

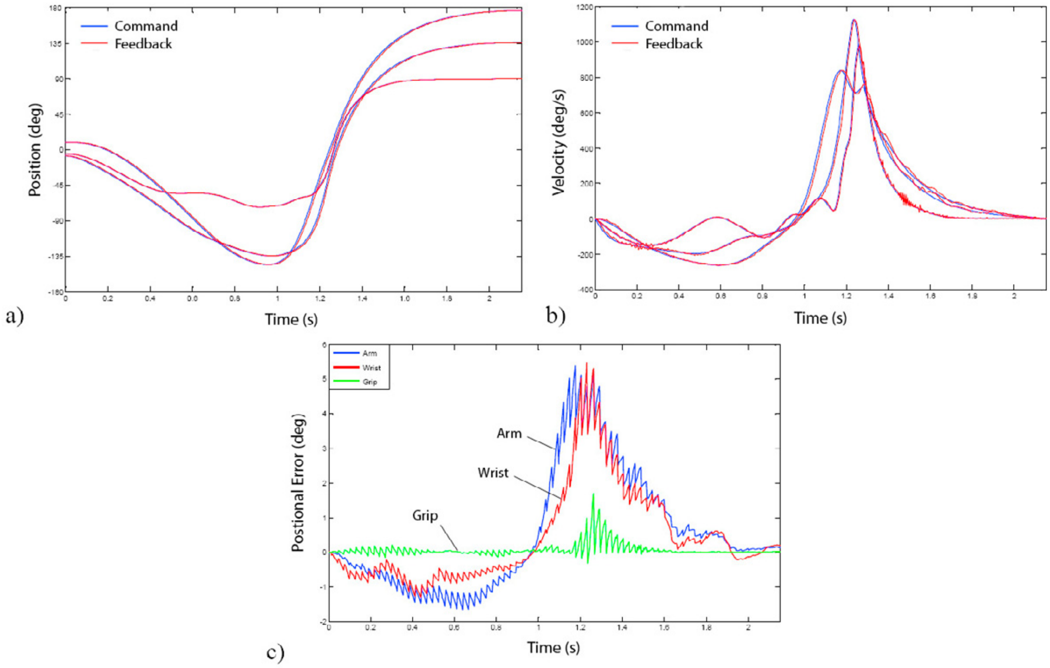

Figure 2 – Comparison of command and feedback data from a simulation of Golfer M2's swing - a) angular rotation, b) angular velocity, c) residual data

The residual data is negative in the backswing and positive in the downswing and follow-through, indicating that the swing motion performed by the robot lagged behind the command positions throughout the swing. These differences are most prevalent in the arm and wrist axes and are strongly related to angular velocity, increasing during the downswing and reaching a peak close to impact, the fastest part of the swing. The residual data was highly consistent across multiple repeat swings and peak positional error was typically between 5 and 8 degrees across all of the golfers.

Shaft deflection was also collected for the robot simulations, again using ShaftLab. Figure 3 illustrates the shaft deflection profiles for two golfers, F1 and M2, along with the corresponding data from the robotic simulations of their swings. Each graph shows the shaft deflection in two orthogonal directions (lead/lag and toe-up/toe-down) for the period from the top of the backswing through to impact, as well as a number of calculated metrics. Point A indicates the time at which maximum deflection occurred (when the bending in both directions is combined).

The shaft deflection profiles for the golfers were remarkably consistent and exhibit characteristics of the different swing types identified by Butler and Winfield [6]. Golfer F1 has a ‘ramp’ profile with shaft deflection gradually increasing throughout the downswing reaching a peak of 2.49 inches (6.32 cm) approximately 0.16 seconds before impact. The profile for Golfer M2 has a more defined ‘single peak’, with a larger maximum deflection of 3.92 inches (10 cm) occurring earlier in the swing. For both golfers, the characteristic ‘kick’ of the clubhead, from lagging behind to leading, can be seen in the data shortly before impact. Differences are evident in the corresponding deflection data from the robot simulations but mainly due to an oscillatory motion, which appears to have been initiated at the start of the swing and has continued throughout. These oscillations do appear to be superimposed on a trend that is similar to the player data but the extent of the oscillations has had an impact on the metrics calculated.

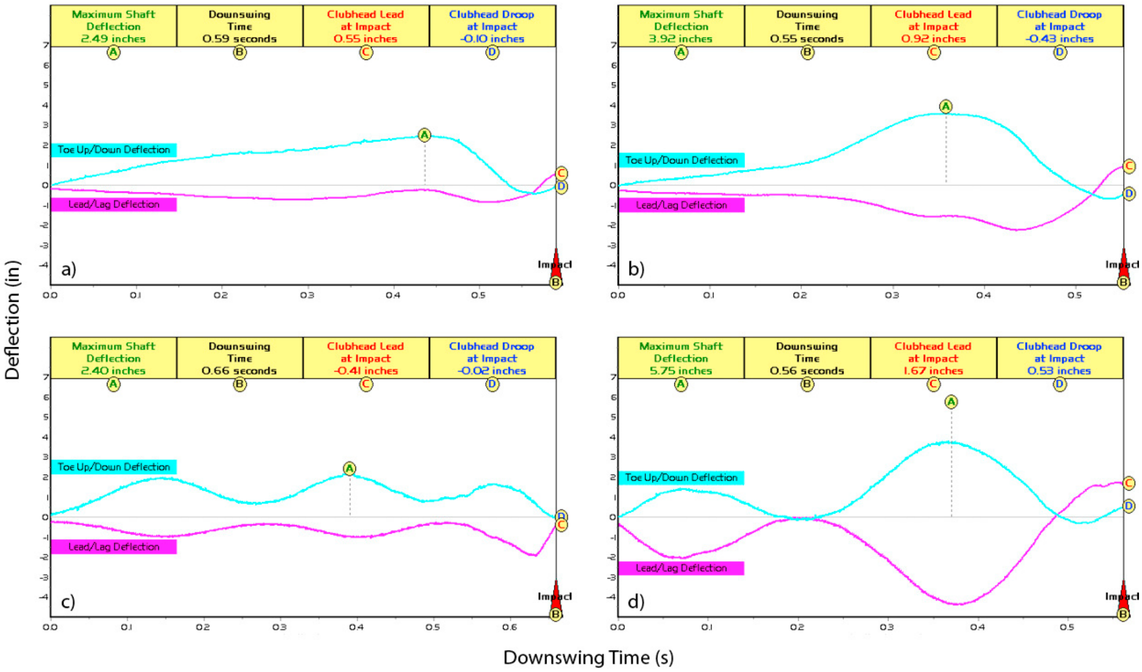

Figure 3 – A comparison of shaft deflection profiles obtained from a) Golfer F1, b) Golfer M2, c) simulation of F1, d) simulation of M2

Maximum shaft deflection is compared between the player’s swing and the corresponding robot simulation for all six golfers in Figure 4. It can be seen that the shaft deflection was typically greater during the simulation, particularly for the golfers that generated greater deformation. Although differences are evident, it is encouraging that the relative trend between the golfers is similar.

4. Discussion

The robot has proved capable of replicating a wide range of swing profiles from a variety of different golfers by using a method developed for generating command files from kinematic data. Although the actual robot motion tends to lag behind the command file data, the differences are relatively small (typically 5° to 8°) especially when compared to the differences between golfers.

Differences in the shaft deflection data were observed, which were mainly due to oscillations of the club during the swing. The cantilever bending mode of the club was excited during initial acceleration due to the mass and inertia of the clubhead mounted on a flexible shaft. These oscillations then continued throughout the swing because of a lack of damping in the system, in particular, at the grip mechanism which rigidly clamps the club in place to prevent it releasing. Commercial golf robots developed to date have addressed club vibration by having an unrealistic backswing that is either much slower, has a long pause at the top of the backswing or by locking the wrist in a fixed position. The aim of this new robot, however, is to produce the most realistic golf swings possible. It is considered essential, therefore, to accurately recreate the motion at the top of the backswing, as this has a large influence on shaft deflection during the swing. These options are, therefore, not considered potential solutions and refinement of the swing profiles to smooth the initial acceleration of the club or modification of the grip mechanism will need to be investigated to overcome these issues.

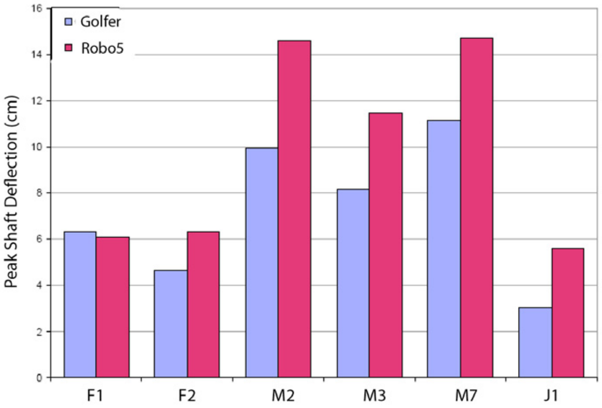

Figure 4 - A comparison of peak shaft deflection obtained from all six golfers and the corresponding simulations of their swings

5. Conclusions

A commercially available golf robot had been successfully modified to provide greater control of the motion and to enable the accuracy of the swing profiles performed to be assessed. Accompanying software has been developed so that command files can be generated from kinematic data measured from a golfer's swing. This has enabled a variety of different swing types to be simulated by the robot. The accuracy of the swing motions performed by the robot was assessed by comparing the command files with feedback data from the motors recorded during a swing simulation. It was found that the robot tends to lag behind during the swing, with the lag increasing with angular velocity of the joint, but the difference was less than 10 degrees even during the fastest part of the swing. Differences in shaft deflection during the downswing were observed between the golfer and corresponding robot simulation due to oscillations of the club initiated during the take-away of the club. These will need to be addressed if the robot is to completely replicate the performance of a golfer.

Although some fine-tuning is required, this paper demonstrates the potential of a golf robot that is capable of recreating individual golfers' swings. This will be a major benefit for manufacturers seeking to customise equipment to a particular type or style of swing.

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