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DESIGN AND ANALYSIS OF A PARALLEL MECHANISM FOR THE GOLF INDUSTRY

Gloria J. Wiens, Eric A. Hunt

University of Florida, Department of Mechanical and Aerospace Engineering
237 MAE-B, P.O. Box 116300
Gainesville, FL 32611-6300, U.S.A.
gwiens@ufl.edu

Abstract

Previous work done in the study of golf club dynamics professes dissatisfaction with robotic testing used to evaluate and compare golf equipment. The main complaint is that the club dynamics measured during a robot swing do not correlate with the same data in a human swing. This paper presents the design and analysis of an alternative to the current robotic testing systems. The viability of a parallel kinematic (two-arm) concept as a robotic testing machine for golf clubs and balls is demonstrated. Human biometric data was used as the basis for determining link geometry as well as motion planning for the swing. Models, simulations, and correlations with human test data were used for validating the design. A demonstration prototype was built to show the interactions and motions of the various components.

INTRODUCTION

The market for golf equipment has grown substantially in recent years mainly due to the advancements in technology and the influx of new golfers from the growing popularity of the sport. Wanting as many advantages over the course as possible, technology has become a more important factor in consideration for the serious golfer. It has subsequently become more important to manufacturers to provide

products that hold a technological edge over their competition. Due to this, there are many different alternatives in the robotic testing of golf equipment.

While, the recently retired pneumatically driven Iron Byron (first swinging robot so named after professional golfer Byron Nelson) consistently produced a certain club head speed for determining balls legal for play (GolfWeb Wire Services, 2001), robots are used in the research and development stages of golf club design as well. Slight modifications to the position of the golf ball enable testing of any region of the club face to find the "sweet spot" and determine what distance and direction variability there is on off-center hits. With a premium placed on perceived technological advancement for the consumer, robotic testing used in the R&D stages of a club's development is highly valuable. Currently, the robotic testing equipment utilizes a single arm that mimics the action of the right arm – bend at the elbow and wrist joints on the back swing to straighten during the downswing and contact the golf ball. The Iron Byron swing consisted only of the downswing and follow-through. The new models of robotic testing equipment are servo-driven, computer controlled, flexible, and available to nearly anyone. For example, MIYAMAE, a Japanese company, currently produces three such models. All of the new robot testers are still single-arm, two-joint systems.

Previous work done in the study of golf club dynamics however professes dissatisfaction with robotic testing used to evaluate and compare golf equipment (Wicks, *et al*., 1999). Ming and Kajitani (2000) modeled the dynamics of a single-armed, under actuated, golf swing robot and developed an optimal motion planning method for maximizing the head speed at impact. The main complaint is that the club dynamics measured during a robot swing do not correlate with the same data in a human swing. To clarify, the differences are well outside the range of experimental error or even human variability. If the equipment tested does not have the same behavior on the golf course with a consumer that it did during testing, the test results mean nothing to the market other than to confuse. Using human biometric data as the basis for determining link geometry as well as motion planning for the swing, a parallel mechanism (two-arm) robotic system approach achieves a more human-like performance. This paper presents the design and analysis of this two-arm alternative to the current robotic testing systems. A demonstration prototype was built to show the interactions and motions of the various components, again emphasizing the prototype capabilities.

DESIGN PROGRESSION WITH HUMAN GOLF SWING DATA

The objective of the work presented in this paper is to determine an alternative to the norm in designing a testing robot. There is a good reason why the current market has only single-arm robots—because they work really well. They're simple, but lack the final direct comparison to real human golfers. In a study of the dynamics of a golf club, A.L.Wicks *et al.* (1999) specifically studied the boundary conditions at the grip of the club. They used finite element and modal analysis to determine the appropriate boundary condition for the modeling of golf clubs. Three boundary conditions were

compared—free-free, hands-free, and clamped-free—where the hands-free is testing using a person holding the grip of the golf club. The conclusion is that the common condition for performance testing of golf equipment—the clamped grip condition—was shown to be inadequate when compared directly with the hands-free case. It is not likely that testing using robots will involve any other method of holding the club when swinging it at over 100 miles per hour, but the two-arm robot offers an alternative by having the robot geometry be more human-like to lessen the impact of having the club held tightly. As was conjectured in the Wicks paper, a pinned condition at the center of the grip may be more useful "since a node line is present for the first several modes [of the free-free case] near that point."

Human Golf Swing Characterization and Modelling

The method used in the design of the parallel mechanism consists first of characterizing the human golfer motion, subdividing the golf swing into the backswing and downswing. Unlike current robotic testing equipment that start the golf swing at the top of the backswing, the backswing was included because it is a significant contributor in a regular golfer's swing. In an ideal golf swing the club, hands, arms, and shoulders all rotate about the fixed spine on the backswing creating tension—building "power." To facilitate maximum leverage the left arm would remain straight throughout the backswing and the downswing motion would be controlled mainly through trunk rotation and left arm action. For the most part, the right arm is along for the ride except near impact when it initiates the "release" of the club or the right forearm rotating over the left forearm in the hitting area.

To simplify the mechanism design, all mechanism motion is assumed to occur in a single plane. This swing plane was identified using the downswing to just after impact data provided by The Biomotion Foundation in West Palm Beach, FL (Hunt, 2002). The data was a compilation of 29 actual markers and 14 virtual markers tracked in 3-D throughout the swing of a 2-handicap male of approximately 50th percentile size (5'10" and 161 lbs). This data was created using a set of high-speed cameras arranged so that they capture the 3-D motion of reflective markers placed at strategic points on a golfer's body. The additional basic assumptions made are: no axial rotation of the arms and club are considered; all rotation is considered about a vector normal to the selected swing plane; contribution in the human swing by the trunk and lower body is not considered in the robotic model; swing motion is arms-only; lateral translation of the entire mechanism is not considered; only a single downswing torque applied about a fixed point located between the right and left shoulder joints; the left elbow is modeled as a fixed joint; and the club position is assumed to never pass parallel to ground.

Figure 1 shows the reflective marker locations on the volunteer's body and club used for determining the various angles of the swing. The club grip is the rubberized portion covering the top portion of the club shaft that the golfer holds when swinging. The hosel is defined as the portion of the club head that is concentrically attached to the shaft.

Since robots are actuated by servomotors and therefore lack any need for "tension building" like a human golfer would, the motion is mostly concerned with the downswing to just after impact. Along those lines, in determining the proper swing plane, the markers for the left arm and club (shoulder (2&3), elbow (5), wrist (7), grip (21), & hosel (22)) were isolated for the downswing and impact. Figure 2 shows the data viewed from beside the golfer (Y-Z plane) looking down the target line (X axis). The shoulder marker does not undergo any out-of-plane rotation during the swing, therefore is not

Figure 1. Markers Locations

subject to error from the planar assumption. This allows for a very accurate assessment of the shoulder plane during the downswing. Notice that in the figure the various markers follow many different paths that could be construed as multiple swing planes, depending on the one chosen. From main stream golf literature, magazines, golf web sites, etc., the golf community would declare the club plane (dashed line) or shoulder plane (solid line) as the measure of the "swing plane." For the two-arm design, the parallel mechanism assumed the swing plane to be the shoulder plane of the human golfer.
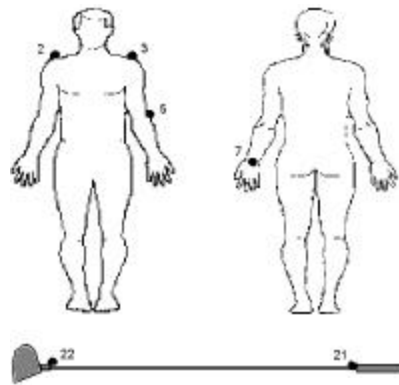
To find what the orientation angle of the plane was to the ground, often called in golf lingo the "lie angle," a linear trend line was added. Using the slope of this trend line, the angle could be directly determined (52.6º from vertical). In the case of an actual golfer, this angle will change depending on which club was chosen—the shorter the club, the more upright the lie angle (angle increases). The assumption for this model is a single club (driver or 1-wood) and a single swing plane orientation (53º) that remains constant throughout the entire swing. Perpendicular to the swing plane is the "trunk vector," one that approximates the spinal column. A golfer's heels will align parallel to the "target line" along the ground, which is represented by the X direction in Figure 2.
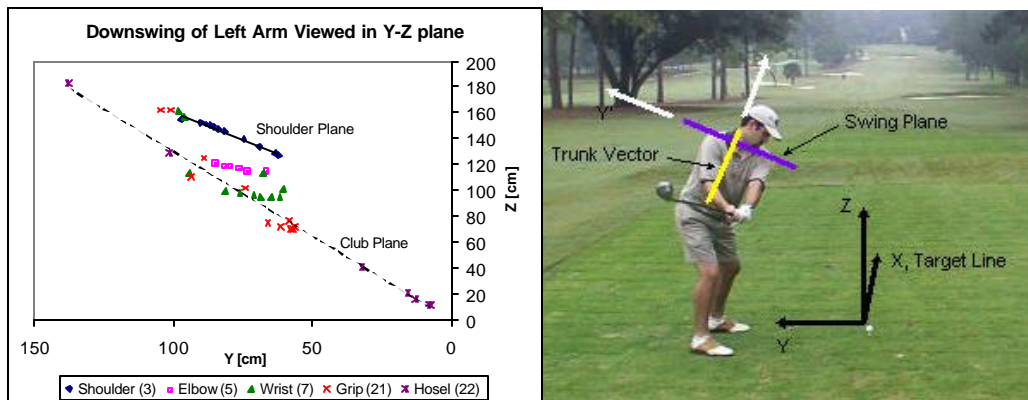

Figure 2. Human Positional Data and Representation of Coordinate Systems

The planar motion assumption requires that the action of the right arm must be modified for the prototype. In a human swing the right arm bends out of plane to about a 90° angle as the left arm collapses onto the chest. With all motion constrained to act in plane, the elbow joint for the right arm was modified to be a prismatic joint or slider. By taking the projection of the complete right arm into the swing plane it appears only to reduce its length, thus the conversion to a linear slider. Another joint that is actuated in the robotic testing mechanism is the wrist. The wrist must have some motion to "cock" the club into a position at the top of the backswing— approximately 100° with the left arm. In a system where there is no backswing included in the motion planning of the robot arm, this can be accomplished manually prior to the test run.

The high speed video system used for the human swing data collected approximately 180 data points every second, meaning one every 0.005555 seconds. This provides the means of determining the speed of the club head during the swing, the most important time being at impact. Using the position for the two points just before and just after impact, the club head velocity was calculated to be 83.9 miles per hour when making contact with the ball. This speed is well below the average club head speed of single digit handicappers for the driver (~100 mph). The computer model was designed to incorporate the necessary motion and torques to produce an adequate club head speed likely in excess of 100 miles per hour. Therefore, the motion of the model cannot be compared to the human swing data on the basis of absolute time. Instead, the information for both the human swing and an ADAMS software simulation model is normalized with respect to the complete swing time, defined as the time from address to impact. Figure 3 shows the human marker data for the right shoulder, left shoulder, left elbow, left wrist, club grip, and club hosel at specific points in the backswing and downswing. Note that for the 0% through the 47.70% lines in the backswing graph the data point for the right shoulder is missing. This was due to an incomplete collection in the original spreadsheet data received
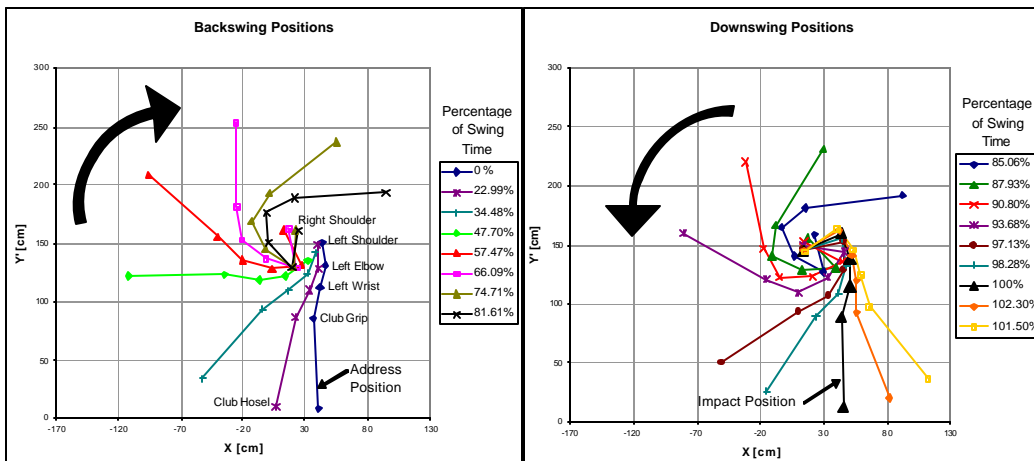

Figure 3. Human Golfer Marker Data Viewed in the Swing Plane

from The Biomotion Foundation. Also notice that the bolder, black polyline in downswing graph indicates the position of impact or 100% of the complete swing.

In determining the geometry of the model, the human positional data for specific markers was used to determine the arm link lengths. Throughout the swing, the distance between two markers was calculated for each data point. These values were summed to find the mean lengths for the upper arms, forearms, and shoulder distance or collar. The lengths for the left control arm are directly incorporated into the model design. The right arm, filling only a support role in the model and prototype, was a secondary design that did not use the direct data calculated from the human swing spreadsheet. Instead it was required only to fit the initial orientation and provide the means of relative motion for the collapsing of the left arm across the chest derived from the normalized angular data from the Biomotion Foundation. The normalized angle data provided was calculated for unit increments of the percentage of swing completion.

The angle of most interest is termed "Left Horizontal Adduction," which is the motion of the humerus (upper arm bone) in the plane perpendicular to the trunk vector. The trunk vector connects two points, one midway between the shoulder joint centers and another midway between the hip joint centers (see Figure 2). As defined earlier, the plane perpendicular to the trunk vector is approximated as the shoulder plane, also considered the swing plane. Therefore, the Left Horizontal Adduction angle is the angle the left arm makes from the left shoulder marker measured clockwise from the positive X axis. The progression of this angle was important to the interaction of the right and left arm linkages where the linear action of the right elbow was used as the input to achieve the desired angles.

The final piece of information that needed to be extracted from the human swing data was the location of the fixed point of rotation. A regular golf swing involves the shifting of weight from a centered position to the inside of the right foot in the backswing, then forward to the left heel on the downswing. However, this model with constant dimensional shoulder only considers the motion of the arms and club around a fixed point of rotation located somewhere in the collar link connecting the shoulder joints. An extension of the original simplification is required in this case. Figure 4 shows the position of the left and right shoulder markers during the downswing as viewed in the swing plane approximately to scale. The task is to locate a point that will yield the smallest deviation in the length between each shoulder motion and the chosen fixed point of rotation. This was tackled through a trial and error method taking advantage of the fact that each shoulder motion is very near a circular arc. A point was selected as the swing center, and then in turn for the two shoulder motions, each data point along with the fixed center yielded a radius. Those radii were statistically analyzed to yield the best swing center with the condition that it had the smallest cumulative percent deviation in those radii (for both shoulder motions together, 1.45% left shoulder and 5.24% right shoulder). Figure 4 shows the final location of the swing center (large dot) as well as projected paths of the shoulder joints.

All the information needed to model the system has been gathered except for the input to the system. The model assumes that the actuation of the mechanism is derived from a torque applied at the swing center. However, values of torque are not available from the positional human swing data. Instead, the input is derived from the angle of rotation of the shoulders. Therefore, the model incorporates the shoulder turn as a linear function of time for both the backswing and downswing separately. After the simulation, the torque was derived using an ADAMS dynamic simulation model of the robotic system and analysis correlated with the normalized human motion data.
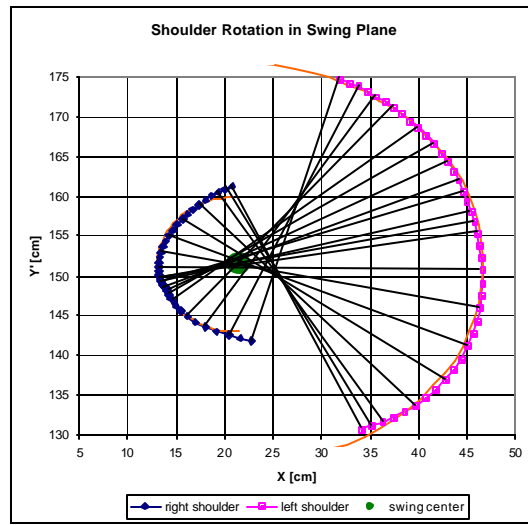

Figure 4. Right and Left Shoulder Rotation in the Swing Plane

Design and Human Data Correlation Results with ADAMS Simulation Model

Using published data available for 50th percentile male (de Leva, 1996), the robots inertial properties were selected and incorporated into the simulation model to provide human like swing characteristics. Figure 5 shows the resulting ADAMS model of the resulting parallel (two-arm) robot and an initial prototype used to demonstrate motion kinematics. The flexibility characteristics of the golf club was also included in the analysis and tuning of the robot's design.

Results. After a number assumptions that reduced the complexity of the design, the main one being that all motion is in a single plane, the results of comparison show a good correlation of the computer model to human swing. The average percent deviation for the entire swing (both backswing and downswing) was 9.6%. The prototype was capable of achieving the range of values for the three main angles of interest: the shoulder rotation, interior arm angle, and wrist cock angle.

SUMMARY

A parallel mechanism (two-arm) robotic testing machine for golf clubs and balls was designed and analyzed in terms of its ability to mimic the action of a human golf swing. Utilizing ADAMS software simulation models generated from the kinematics and inertial parameters extracted from the study of biometric data of a human golf swing and the literature, the viability of a parallel mechanism (two-arm) concept for

use as a robotic testing machine for golf clubs and balls has been demonstrated. An un‑powered demonstration prototype was built to show the interactions and motions of the various components. Future work is the fabrication of a fully operational prototype, implementation of various control methodologies and experimentally validating the above results.

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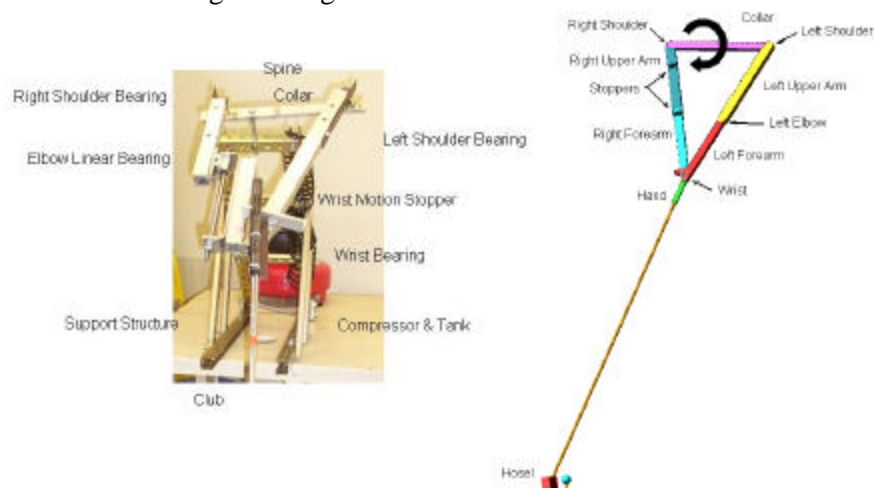
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Figure 5. Golf Robot Prototype and ADAMS Simulation Model