



Biomechanics of the golf swing using OpenSim

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ABSTRACT

A study was conducted to investigate the underlying mechanisms involved in the dynamics of body motions during the golf swing. A series of model simulation programs were developed in OpenSim to control the characteristics of the biomechanical model of the body. The resultant model parameters were put in an Excel file, which allowed these parameters to be modified. OpenSim model simulation run was paused at various points of the golf swing and screenshots were taken. MATLAB was used to find the positional value of the center of clubface for each screenshot and the Euclidean distances of the clubhead position between poses. A series of simulation trials were then conducted using various time increments between the poses in order to calculate the clubhead velocities. Three of these trials were selected to illustrate the swing patterns of players of varying skill levels ranging from basic beginner to highly-skilled. These simulations using OpenSim can serve as a platform for understanding the dynamics of body motions in sports and biomedicine.

1. Introduction

The use of sequential motion images is one of the most common means to convey information regarding body biomechanics [21]. In the field of sports, video analysis is frequently used to assess player movements. For example, in gymnastics, performance is rated by analyzing user movements through image processing techniques [15]. In dance, skills are evaluated by assessing posture and other variables that are influenced by rhythm and timing [5]. Similarly, in the field of golf, studies have been conducted using visual analysis to score an individual's golf swing motion through the implementation of various technologies such as Microsoft Kinect [19], the Wii [9] and object tracking [20]. While these methods are generally used for rating performance in elite players, they can also be useful for assessing errors in body motions of amateurs to provide feedback regarding corrections to these movements.

The motions involved in a golf swing are some of the most dynamically complex movements in sports [11]. It requires the execution of numerous sequential elements. When produced precisely, this results in a great golf shot, but with only minor deviations results in a poor golf shot [11]. There has been considerable debate on the dynamics of a golf swing [22], but most researchers and experts in the field agree that aspects like balance, timing, hand placement, and stance are key in the effective development of a consistent golf swing. This complexity is further exacerbated by the fact that the average age of a golfer is 43 years old [16]. Not only is there a wide range in playing ability and age

of players, but the game is becoming culturally diverse as well [10]. There is nevertheless an economic constraint to entry into playing golf, as the average golfer spends approximately \$3000 annually [13]. As of 2010, roughly 20% of players are from a minority group [10]. In addition, it is estimated that the number of U.S. golfers would grow by about three million between 2010 and 2020. This is a growth rate of about 1%, similar to the forecasted growth rate of the general U.S. population [1]. Presently, there are 23.8 million golfers in the U.S. [4].

People of all sizes and athletic ability can take part in this sport. For this reason, an individualistic approach to learning is required to aid with movement correction in the golf swing. A recent study focusing on analyzing the efficacy of various methods of learning the golf swing found that video feedback was the most effective [6].

Several commercial systems have been developed as instructional tools for improving one's golf swing [7,17]. These systems analyze the problem areas in a user's golf swing by comparing them with the swing patterns of one specific professional or the average of many professionals. For example, Swinguru analyzes the user's swing by focusing on the body movements through automatic motion capture. The program then provides instantaneous feedback on areas of improvement in their swing by comparing them to the movements of a specific professional player [7]. A similar system, SwingClone, assesses a user's swing and informs the user about problems by comparing them to the average movements of the top 100 professional tour players through the manipulation of synthetic models [17].

While these commercial systems provide useful information about a

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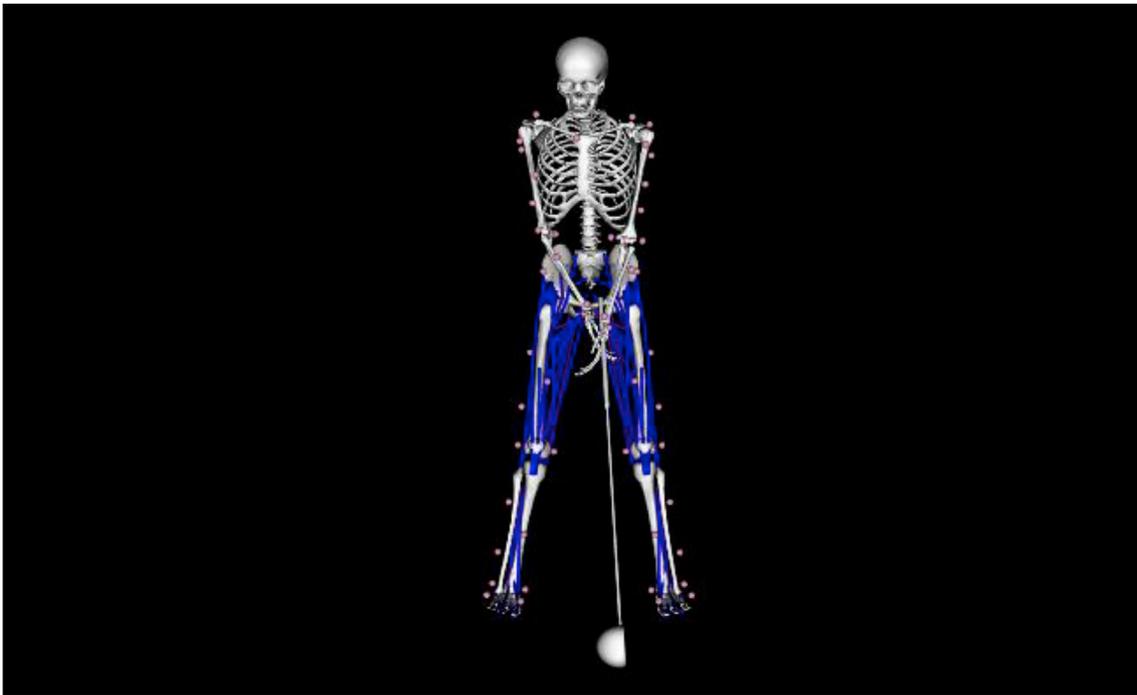


Fig. 1. Close-up view of the Rajagopal model [14] incorporated with a golf club in the starting position of a golf swing.

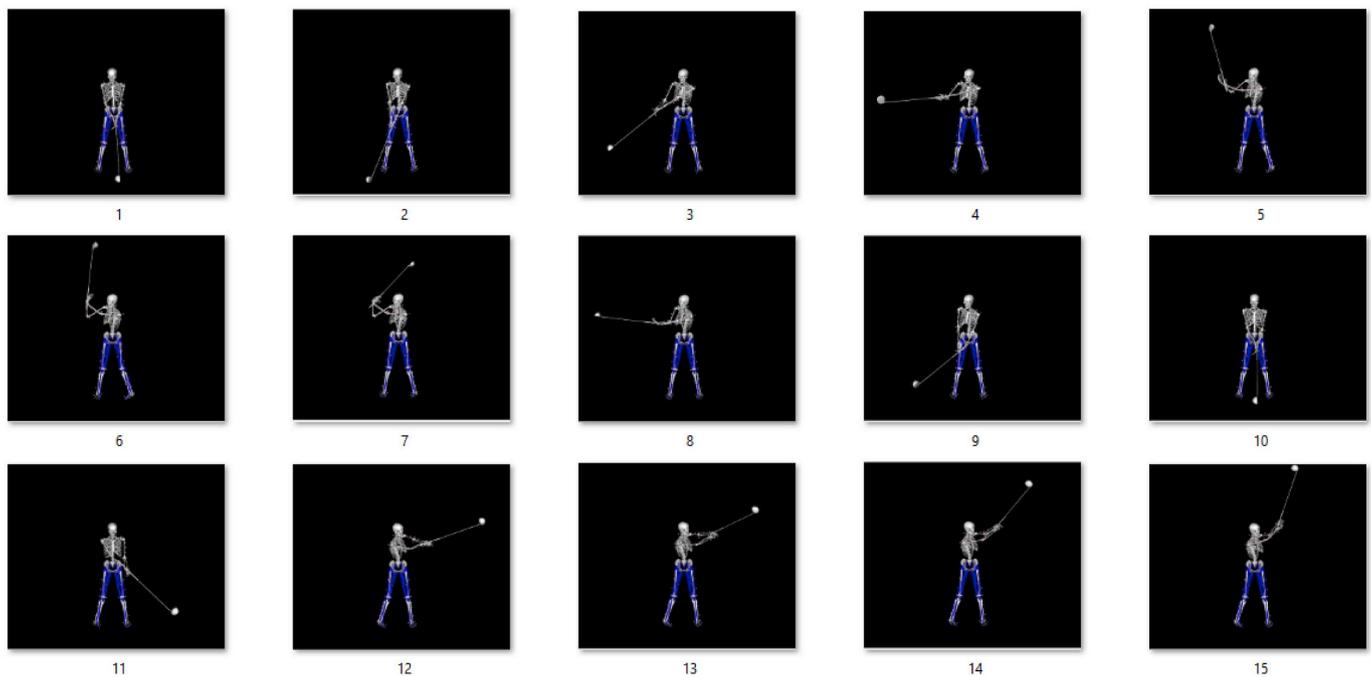


Fig. 2. The array of pictures represents the sequence of movements in a golf swing. Pictures 1 through 7 are the poses for the backswing and pictures 8 through 15 are those for the forward swing. Based on swing sequence shown in Ref. [3].

user's golf swing, they contain standalone programs that do not allow modeling researchers to modify and control the parameters in the models. What is needed is a way to vary the different components of a golf swing to specifically reflect the skill levels of golf players who have different anthropometrics, muscular strength, and flexibility [18]. The impetus for our research is to investigate the use of an open source platform to control biomechanical motions during a golf swing by varying the model components.

2. Methods

OpenSim is a free open-source software platform for creating biomechanical models. The program allows the user to manipulate the complex motions and forces involved in musculoskeletal systems. Users of this technology can address fundamental issues in movement science and apply this to critical areas of rehabilitation medicine, including stroke, spinal cord injury, cerebral palsy, prosthetics, orthotics, and osteoarthritis [12]. In the past, it was rather difficult to accurately model the inner mechanics of the body during dynamic motions, but

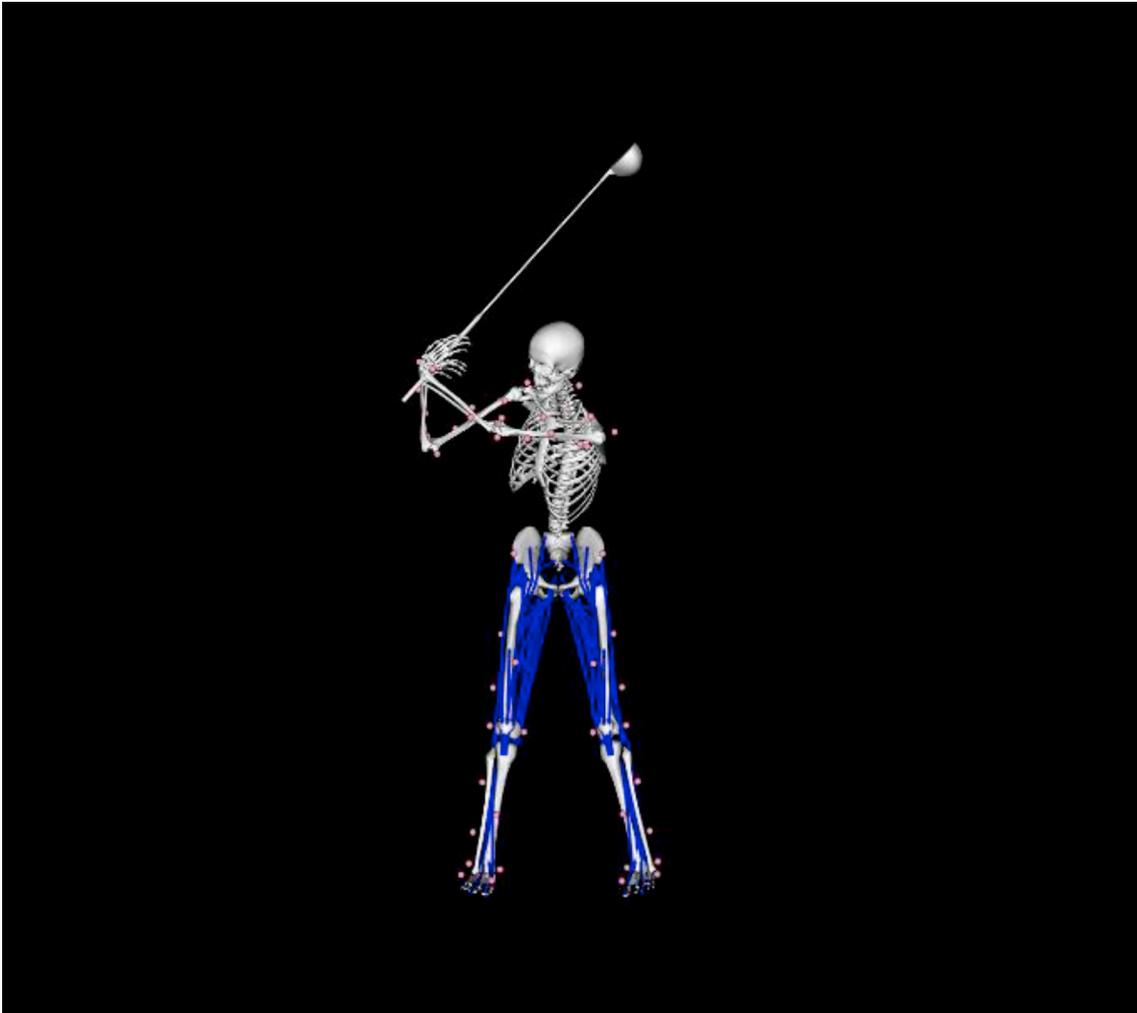


Fig. 3. A (Top). The image is a close-up version of pose 7 in Fig. 2. It shows an inward turn of the left knee and foot and considerable rotation of the torso and shoulders, along with a tucked in right elbow and extended left arm, to set the golf club at the top of the backswing. B (Bottom). The image is a close-up version of pose 15 in Fig. 2. It shows an inward turn of the right knee and foot, and considerable rotation of the torso and shoulders along with a high hand and arm finish.

OpenSim made it accessible to the researchers. While OpenSim was originally designed to aid in the modeling of medical processes, it has also been used for the analysis of body movements involved in various sports. For our study, we manipulated the parameters of the OpenSim models of the body components, along with the golf club, to simulate a wide range of motions during the golf swing.

OpenSim comes with many default features, some of which, however, are difficult to comprehend at first. But after some careful investigation, they become understandable. Indeed, one of the contributions of this article is to provide clarification on the appropriate procedures to properly run OpenSim.

When setting up the OpenSim model, a useful feature is that any particular parameter can be varied over a range of angles, and the effect is simultaneously seen in the model figure. By varying the parameter over a range of values, either by explicitly typing in the values or by moving a control bar, the sensitivity of the variation on the range of model movements can be observed. Starting with the initial model, model parameters can be modified to create a new pose. The model parameter values are then saved in a text file, which is unique for a particular pose. In this way, multiple sequential poses can be created, and since the parameters are saved in a file, these poses are completely repeatable.

One of the most important features is the “model” component. The program actually comes with many default downloadable models for various parts of the body. One unique aspect is that it is possible for the

user to modify and even create their own model. Since the codes involved in many of the models are quite cumbersome, it would be much more efficient to modify an already existing model to suit the user's specific purpose. For this project, a model of a golfer was needed. It turns out that a model of the entire human body called the Rajagopal model [14] was specifically created for use within OpenSim.

Another useful aspect of OpenSim is the ability to create body motion. Detailed descriptions of how to include body components and to create motion files are provided in the next two sections below. The descriptions are provided in great detail because the steps must be followed precisely.

When a model is opened, its attributes will appear in the Navigator tab of OpenSim. The Navigator tab allows the user to see all the parts involved in the model. If a particular motion were to be added to the model, it would also appear in the Navigator tab. Double-clicking any part of the Navigator tab will open the Property tab, which will show all the values for the given anatomical part. Another major component of OpenSim is the Coordinates tab. The Coordinates tab contains all the body components in the model that are linked together to synergistically move in a coordinated fashion. Each of the body components comes with a default value, which represents its location and rotational angles relative to a parent joint reference. This simplifies the simulation process because one only needs to alter the default values to allow movements of various components of the model in different ways. The Coordinates tab also contains a Poses button, which allows the user to

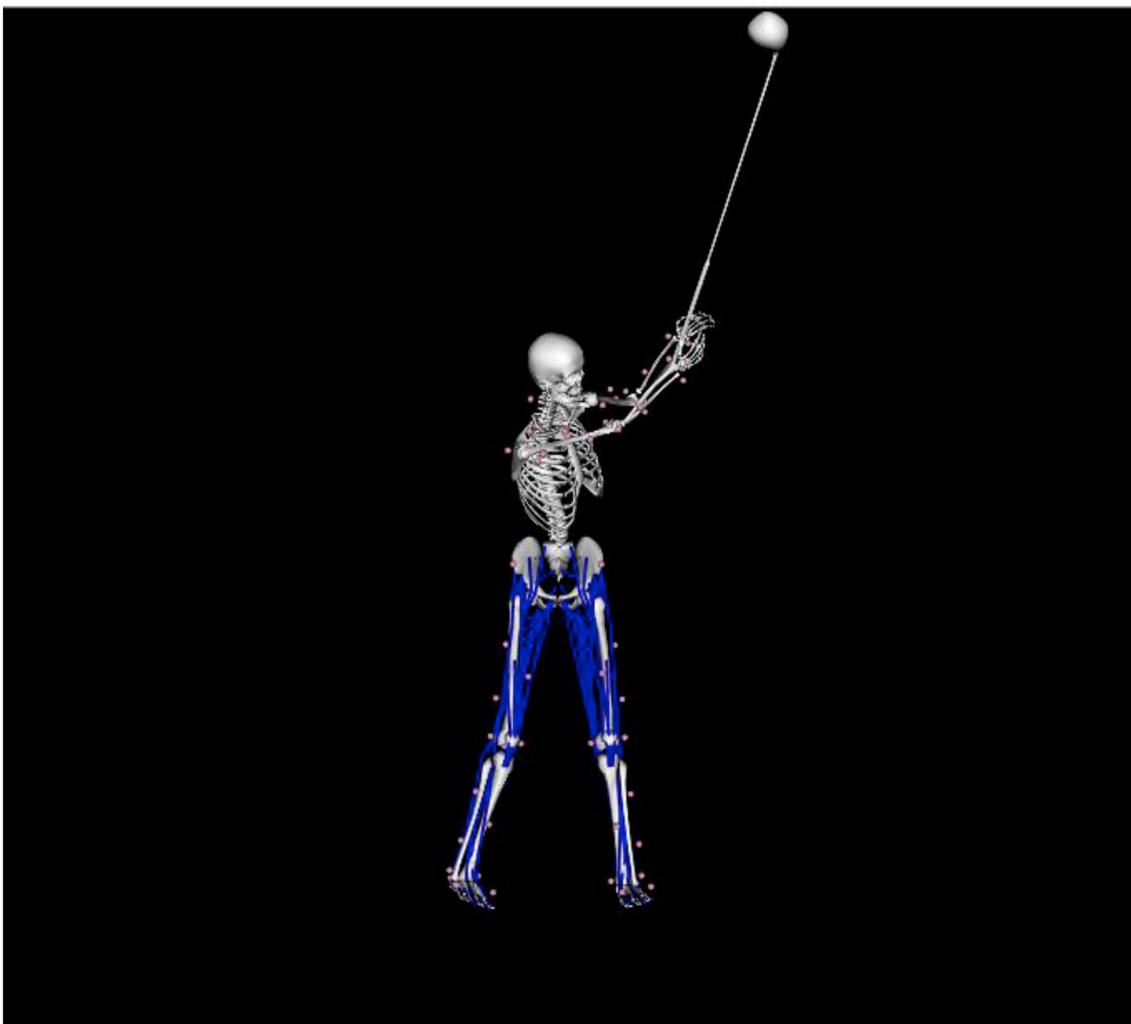


Fig. 3. (continued)

Table 1

Delta-t values between successive poses (seconds). The poses correspond to those in Fig. 2. The Trials correspond to (1) beginner (2) advanced player and (3) highly-skilled player.

Trial	Poses														
	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	
1	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	
2	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.15	0.075	0.035	0.15	0.15	0.15	0.15	
3	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.06	0.03	0.0175	0.05	0.05	0.05	0.05	

save all the values in the Coordinates tab into a single pose. If multiple sequential poses were to be combined into a single motion data file, it is then possible to create dynamic motion of the body. The parameters in the motion file are most easily manipulated when they are organized within an Excel file.

2.1. Connect golf club to human body

The human body model was obtained from a user-built OpenSim file called the Rajagopal model [14], while the golf club model was obtained from an open source file [23]. The OpenSim models are designated as “.osim” files. Importantly, it is possible to edit these models using any text editor. The Rajagopal model [14] constitutes the main body of the text file. The golf club model [23] was then added to the Rajagopal model [14] using the instructions provided by an open-source software program on how to embed an external object into a

larger model [8]. The code was developed by substituting the example object parameters provided in the instructions with the golf club model parameters. In order to make specific changes to the shape and orientation of the golf club relative to the body, the parameters were modified in the text file and adjusted incrementally until the desired club configuration was attained.

2.2. Create and modify motion file

The instructions for modifying the motion file is as follows: Once the model is uploaded in OpenSim, move the model to a desired location on the screen using the values in the Coordinates tab. Save the pose by clicking Poses, then New, and then provide a name for the pose. After that, press the Run button and immediately press the Stop button. The reason the Stop button is pressed immediately is that only the first line corresponding to the first time-instance, or a snapshot of the pose, is

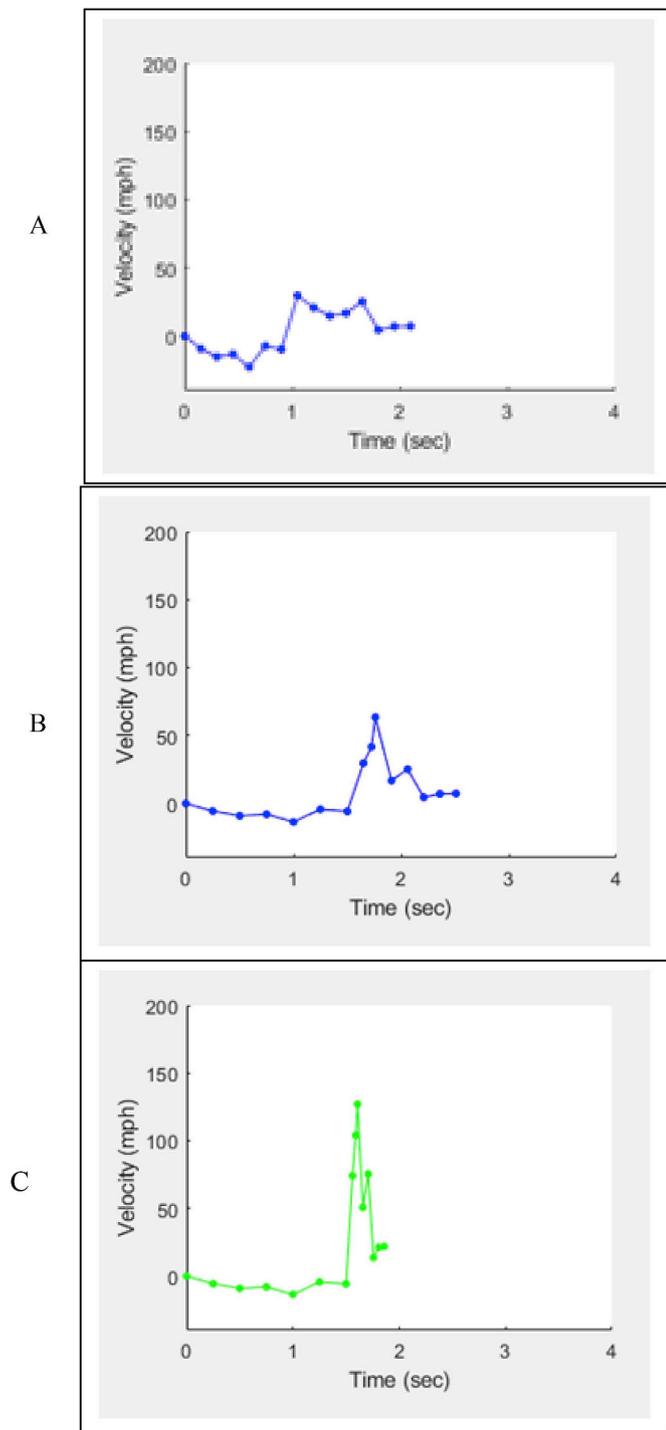


Fig. 4. Model simulation dynamic clubhead velocities for (A) beginner, (B) advanced player, and (C) highly-skilled player.

needed for parameter evaluation. The reason to immediately press the Stop button is to not generate an unnecessarily long file. A new Results will show up in the Navigator tab under Motions. Save the Results file as a motion (.mot) file. Open that file in Excel and delete everything in the file after the first row of data. Again, the first row of data points contain the values for the pose. Then change Nrows to 1, and save the file. This file will be added upon subsequently so it will have all the later poses. Repeat the steps mentioned above to create another pose. Copy and paste the first line of data from the new file into the original file below all previous data and increase Nrows by 1. Change the time value for the new pose to the desired real time. Once all the poses are

saved in the same file, go to OpenSim and open the model. Then click on File, Load Motion, to import the motion file that was edited in Excel. This file should contain all the poses. Once the file (shown as Results in OpenSim) is loaded, click on the Play button to see the motions with all the poses. If changes need to be made to the movement dynamics, the Excel file can be used to edit the poses since the values in the Excel file correspond directly to the coordinate values in OpenSim.

The next step involves the use of a MATLAB program. Once the motion looks correct, screenshots are taken at each successive poses at specific times during the OpenSim simulation. Save all the screenshots in the same folder. The MATLAB program allows the use of a cursor to mark specific points on the screen. Mark the center of the clubhead manually for each screenshot, and use the program to calculate the Euclidian distance between the center marks between successive poses. Then, specify the time values for each pose to calculate the velocities.

3. Results

Combining the Rajagopal model [14] with the golf club model [23] and manipulating the model parameters resulted in the sequence of body and club positions shown in Figs. 1, 2 and 3A,B. It was assumed that the body model was 6 feet tall for the purpose of calibrating clubhead displacements. The positional information of the center of the clubface in each of the poses was transcribed and used in a MATLAB program for determining club-head velocity using the Euclidean distance between poses and the corresponding time increment (which is selectable for different trial conditions).

By using different time parameters, a number of swing scenarios were created. Three of these trials were selected to illustrate the main differences between 3 levels of playing skills (see Table 1). In the trials, the categorization of the sequence of poses being part of the backswing or forward swing (downward transition and follow-through) were determined manually. The first trial had a constant delta-t (between sequential poses) of 0.15 s throughout the swing. This corresponds to a beginner. The second trial had a constant delta-t of 0.25s during the backswing (poses 1–7), but decrease in delta-t during the downward transition (poses 8–11), and a constant delta-t of 0.15s during the follow-through (poses 12–15). This corresponds to an advanced player. The final trial had a constant delta-t of 0.25s for the backswing, with a further decrease in delta-t during the downward transition and a short delta-t of 0.05s during the follow-through. This corresponds to a highly-skilled player.

Fig. 4A–C shows the OpenSim simulation time courses corresponding to the delta-t values in Table 1. The beginner player (Fig. 4A), with a constant delta-t of 0.15 s, exhibits a relatively low peak velocity of 30 mph. On the other hand, for the more advanced player (Fig. 4B), with decreased delta-t during the downward transition, exhibits a higher peak velocity of 64 mph. Moreover, for the highly-skilled player (Fig. 4C), with a further decrease in delta-t during the downward transition, exhibits a much higher peak velocity of 127 mph. Note that the delta-t for the backswing was the same for both the advanced and highly-skilled players. Also, the delta-t for the follow-through was the same for the beginner and advanced players, whereas it was shorter for the highly-skilled player. The categorization of the sequence of poses being part of the backswing or forward swing were determined manually.

A sensitivity analysis was undertaken. But since there are over 200 parameters in the model [14], it would be an enormous task to do this for all the parameters. Therefore, two sample parameters (left wrist and left arm abduction) were selected to provide a representative sensitivity analysis (Fig. 5A and B). The simulations are shown over a range from -90 (backswing) to $+90$ (forward swing) in 30 degree increments. For clarity of viewing, the right arm and hand have been hidden in the simulations.

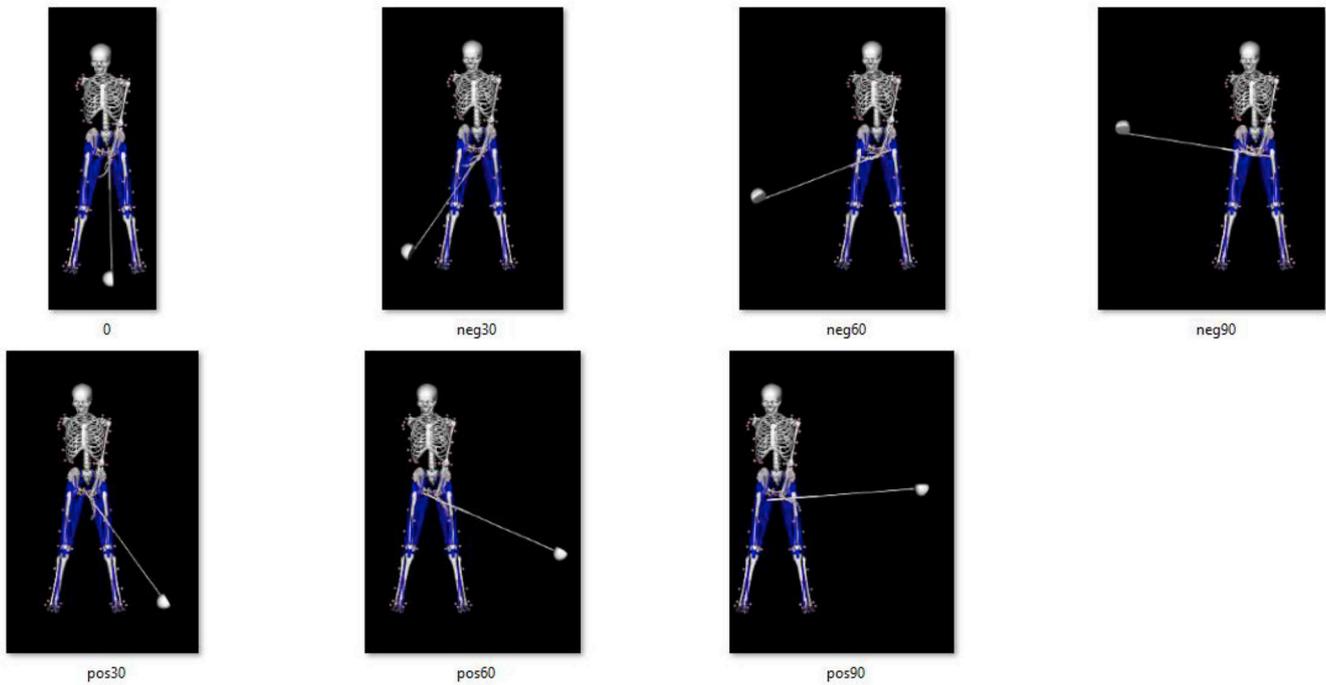


Fig. 5. A (Top Sequence). Sensitivity analysis of the left wrist parameter over a range from -90 (backswing) to $+90$ (forward swing) in 30 degree increments. B (Bottom Sequence). Sensitivity analysis of the left arm abduction parameter over a range from -90 (backswing) to $+90$ (forward swing) in 30 degree increments.

4. Discussion

The goal of our study was to provide a roadmap for future investigations into dynamic body motions in sports and medical activities. This was a complex and elaborate technique which required a concerted effort in coordinating different modeling and programming methods with the detailed characteristics of various aspects of OpenSim. Some of the steps required non-conventional approaches to extract the necessary data in order to properly analyze and execute the model simulations. Nevertheless, the effort was worthwhile since we

were able to control the modeling parameters to properly simulate dynamic body motions of different individuals.

The usefulness of the techniques employed in this study is that one can simulate the control of the motions of specific body components to provide a detailed composite of model parameters that result in the movements of a particular player. Parameters such as position, velocity, and angle of the muscle can reveal important relationships between muscle groups, joints, and body components during the golf swing, especially just prior to impact.

In OpenSim, the human model was obtained via experimental data

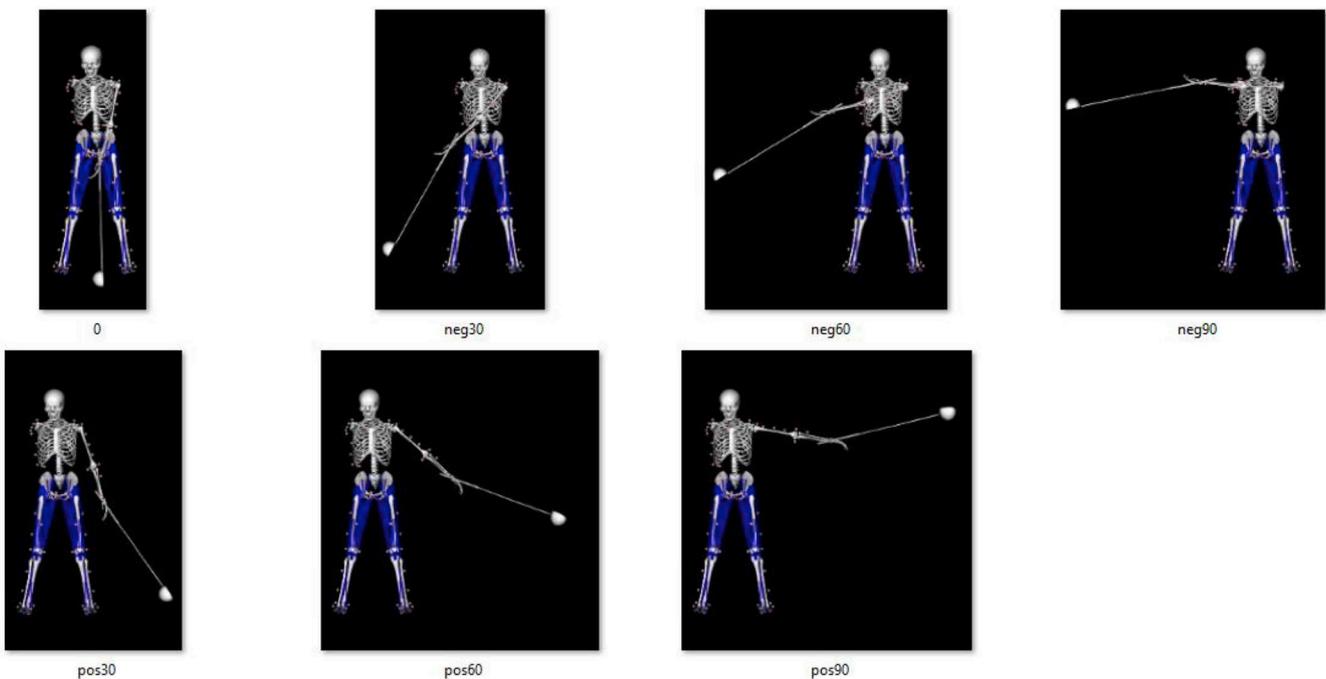


Fig. 5. (continued)

and converted using inverse kinematics and inverse dynamics. The techniques used in the study can be used to explore variations to the original model via parameter modifications. Sensitivity analysis can be applied to examine variation in model parameters on changes in body components. For example, scaling of body height could be used to determine optimal height for performance in sports such as golf and tennis. Variation in club length could be used to determine the fastest clubhead speed in relation to body size. Also, variation in timing differences in joint angle changes during different points of the swing arc could provide information regarding optimal swing speed. Moreover, variation in posture during initial address and throughout the swing can provide information regarding changes in 3-dimensional view of the swing path.

In finding a way to simulate and analyze the data for a golf swing, two main approaches were considered. One was to conduct experiments in a laboratory and then gather the data using various equipment. The other option was to simulate the motion using a software program. Both options have positive and negative aspects. The laboratory approach allows one to create an experimental environment and acquire physical data, as well as provide more freedom in terms of experimental design. On the other hand, there are substantial costs involved in implementing these experiments. For the software approach, it allows one to simulate various scenarios as well as provide insights into the characteristics of body and mechanical systems, and at minimal cost. On the other hand, the lack of the ability to directly generate human subject data limits one to use those that were attained by others. Both approaches are viable solutions. Ultimately, it was decided that the software simulation option would be more optimal in actually creating and analyzing the components of a golf swing in a variety of individuals. Moreover, it turned out that OpenSim was a powerful software platform that was available for performing these simulations.

The average golf swing speed for different levels has been categorized as ranging up to 70 mph for the beginner, 70–95 mph for the advanced player, and 95 to 110 mph for the highly-skilled player [2]. It should be noted that these are estimated ranges. In our simulations, the peak velocities were 30 mph for the beginner, 63 mph for the advanced player, and 127 mph for the highly-skilled player.

Regarding scaling of body and club components, there was no specification in the Rajagopal model [14] for the height of the human model, so it was estimated using a round number of 6 ft for an average male golfer. It would be possible to scale for a different height, which would result in slightly different clubhead velocity values. But the overall pattern of the velocity traces should remain the same. In golf, clubhead size varies considerably. But the important part is the center of the clubhead, which is used to calculate clubhead position. Changing clubhead size would result in slight changes in clubhead velocities. But again, the overall pattern of the velocity traces should remain the same.

Similar to many other sports, golfers range in ability from a basic beginner level to a highly-skilled level. This is illustrated in Fig. 4A–C. Fig. 4A represents the clubhead time course for a beginner. The graph shows how the swing lacks velocity, and does not exhibit any spike in velocity during the downswing. It also is very quick and does not provide any significant impact on the golf ball. Fig. 4B represents a more advanced player. The graph shows a dramatic spike in the velocity during the downswing. However, the swing is somewhat slow in the follow-through phase, taking some time to complete. Fig. 4C represents the highly-skilled player. Similar to the advanced player, the swing time-course has a dramatic spike in velocity during the downswing. However, the highly-skilled player shows a much higher peak

velocity and the swing finishes much faster. This is mainly due to a much smaller delta-t values just prior to impact.

Comparison with experimental data taken on golfers at various skill levels would be very useful for deciphering the subtle but specific variables that differentiate an ordinary golfer from a highly-skilled player. Moreover, the model component specifications can be used to pinpoint parameters of the golf swing related to deficiencies and give insight into biomechanical factors that may not be obvious to the casual observer. This is an area for future study using our modeling technique. It is hoped that the specific guidelines of our technique, through OpenSim, can serve as a platform for further investigations in the simulation of complex body motions in sports and biomedicine.

References

- [1] J.F. Beditz, J.R. Kass, *Golf Participation in America, 2010-2020*, National Golf foundation, 2010.
- [2] J. Bowden, Average golf swing speed chart, *Swingmangolf* (April 11, 2018), <http://www.swingmangolf.com/average-golf-swing-speed-chart-2/>.
- [3] E. Demircan, T. Besier, Muscle force transmission to operational space accelerations during elite golf swings, *IEEE Int. Conf. Robot. Autom.* (May, 2012) 1464–1469.
- [4] D. Dethier, 15 numbers you need to know about the U.S. golf economy, <http://www.golf.com/tour-news/2018/05/01/15-numbers-you-need-know-about-us-golf-economy>, (2018).
- [5] S. Essid, D. Alexiadis, R. Tournemene, M. Gowing, P. Kelly, D. Monaghan, P. Daras, A. Dreameau, N.E. O'Connor, An advanced virtual dance performance evaluator, *IEEE Int. Conf. Acoustics Speech Signal Process.* (2012) 2269–2272.
- [6] M. Guadagnoli, W. Holcomb, M. Davis, The efficacy of video feedback for learning the golf swing, *J. Sports Sci.* 8 (2002) 615–622.
- [7] GURU Inc, *My Swinguru*, <http://www.swinguru.com>, (2013).
- [8] J. Hicks, Jun 27, 2018. <https://simtk-confluence.stanford.edu:8443/display/OpenSim33/Example+-+Model+Editing>.
- [9] S.K. Huang, K. Kuo, Y. Lin, A golf swing analysis system using Wii balance board and Kinect sensors for novice players, *Multimed. Tool. Appl.* 74 (2014) 10679–10696.
- [10] R. Lake, 23 golf player demographic statistics that might surprise you, <https://www.creditdonkey.com/golf-player-demographic.html>, (2015).
- [11] S.J.B. Mather, *Physics and mechanics of the golf swing*, in: G.K. Hung, J. Pallis (Eds.), *Biomedical Engineering Principles in Sports*, Kluwer/Plenum Publishers, 2004, pp. 47–74.
- [12] NCSRR, 2010. [opensim.stanford.edu/work/index.html](https://www.opensim.stanford.edu/work/index.html).
- [13] T. Pringle, The demographics of golf- inside the mind of a golfer, www.americangolf.com/blog/mulligans/the-demographics-of-golf-inside-the-mind-of-a-golfer, (2014).
- [14] A. Rajagopal, C.L. Dembia, M.S. DeMers, D.D. Delp, J.L. Hicks, S.L. Delp, Full-body musculoskeletal model for muscle-driven simulation of human gait, *IEEE (Inst. Electr. Electron. Eng.) Trans. Biomed. Eng.* 63 (2016) 2068–2079 https://simtk.org/projects/full_body.
- [15] J. Shin, S. Ozawa, A study on motion analysis of an artistic gymnastics by using dynamic image processing, *Proc. IEEE Int. Conf. Syst. Man Cybern.* (2008) 1037–1042.
- [16] M. Stachura, The NGF's annual golf participation report uncovers favorable trends for the game's future, <https://www.golfdigest.com/story/the-ngf-annual-golf-participation-report-uncovers-favorable-trends-for-the-games-future>, (2017).
- [17] SwingClone biomechanics, <http://apps.microsoft.com/windows/en-us/app/swingclone-biomechanics/b8f42d7d-2def-40c5-b45d-885585b085e7>, (2013).
- [18] L. Torres-Ronda, A. Delextat, J. Gonzalez-Badillo, The relationship between golf performance, anthropometrics, muscular strength and power characteristics in young elite players, *Int. Sportmed J.* 15 (2014) 156–164.
- [19] W. Wang, H. Ku, S. Tsang, Using clustering algorithm to validate the golf backswing action simulated, *Appl. Math. Inf. Sci.* 10 (2016) 747–753.
- [20] L. Weixian, L. Xiaoping, D. Mingli, Z. Lianqing, Golf video tracking based on recognition with HOG and spatial-temporal vector, *Int. J. Adv. Robot. Sys.* Sagepub (June 2017) 1–8 <http://journals.sagepub.com/doi/pdf/10.1177/1729881417704544>.
- [21] A.M. Williams, N.J. Hodges, Practice, instruction and skill acquisition in soccer: Challenging tradition, *J. Sports Sci.* 23 (2005) 637–650.
- [22] D. Williams, The dynamics of the golf swing (with conclusions of practical interest), *Q. J. Mech. Appl. Math.* 20 (1967) 247–264.
- [23] Zaurian868, *Golf Clubs 3d Model*, (May 9, 2015) <https://free3d.com/3d-model/golf-clubs-82208.html>.