Model created in COMSOL Multiphysics 6.4

Mechanics of a Golf Swing

Introduction

How well you can strike a golf ball is not only determined by your muscle strength, but more importantly it is influenced by several other factors involved in the mechanics of the golf swing. The outcome of the golf stroke is basically determined by the movement of the club head just prior to the impact with the ball.

In this example, a multibody analysis of a golf swing is performed using the Multibody Dynamics interface in COMSOL Multiphysics. The aim of the analysis is to maximize the club head speed just prior to the impact with the ball. The wrist torque, which has an important role to play in improving the outcome of the stroke, is varied parametrically to see its effect on the club head speed.

Model Definition

ARM-CLUB (TWO-LINK) VS SHOULDER–ARM–CLUB (THREE-LINK) SWING MODEL

A simple way to simulate the golf swing is by using a two-link model, where the arm and the club are the two links connected together by a hinge joint. In this model, the arm rotates about a fixed point, located at the base of the neck, and the club rotates about the wrist joint relative to the arm.

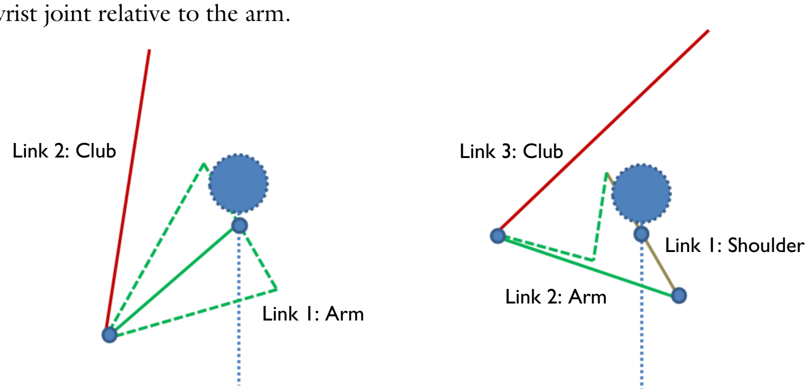

Figure 1: Diagram of two-link (left) and three-link (right) swing models.

The two-link model does not allow a sufficiently long backswing and is not actually a true representation of a real-life golf swing.

A better representation is the three-link model, which also includes the shoulder as a separate link. Adding one more link eliminates the problem related to the backswing.

Hence, this three-link model is used in this analysis. To also consider the flexibility of the club shaft in a simple way, it is divided into two parts: the grip and the club. These parts are connected through a hinge joint with finite stiffness and damping.

SWING MECHANICS

The torque profile applied by different body parts (shoulder, arms, and wrist) is assumed. It is limited by the maximum torque capacity of the respective parts. Among all applied torques, the wrist torque has quite an important role to play in getting the strike right.

While simulating the downswing of the club, the entire swing can be divided into two phases. In the first phase, arm and club rotate about the fixed point as a rigid assembly. In this phase, the arm and club are folded to minimize the inertia about the center of rotation, which allows the development of maximum angular velocity for the given arm-torque capacity. Here, the wrist is cocked to the maximum possible angle and the applied wrist torque tries to hold back the club in this position against the other two torques.

In the second phase, the wrist torque starts helping the shoulder and the arm torque by pushing the club forward to increase the club head speed to its maximum. The instance when the wrist torque changes its role is a crucial parameter in determining the stroke quality. To see its effect on the club head speed, the wrist torque switch time is varied parametrically.

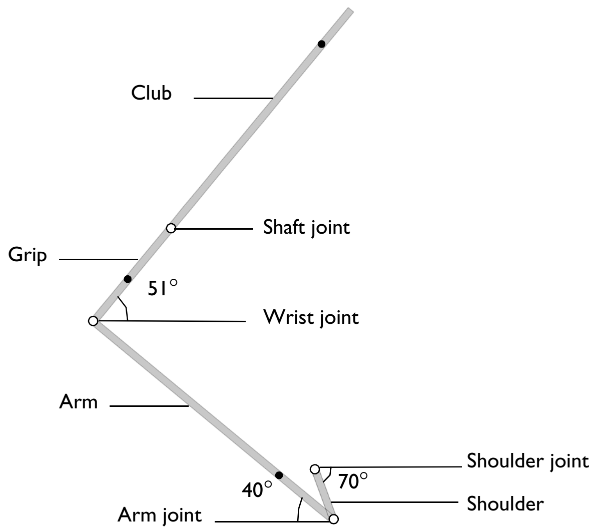

Figure 2: Model geometry: center of mass of each link is also shown.

GEOMETRY AND CONNECTIONS

The model geometry is shown in Figure 2, which consists of four links: the shoulder, arm, grip, and club. These links are connected to each other by four hinge joints. The initial values, also representing the limiting values in this case, of shoulder angle, arm swing angle, and the wrist-cock angle are also shown in Figure 2.

The geometric data, inertial properties, and joint properties are taken from Ref. 1. All the links are modeled as rigid bodies and their length, mass, and moment of inertia about the center of mass are given in Table 1.

TABLE 1: LENGTH, MASS, AND MOMENT OF INERTIA OF LINKAGES

Linkage	**Length (m)**	**Mass (kg)**	**Moment of inertia (kg·m^2)**
Shoulder	0.150	-	0.800
Arm	0.854	8.644	0.354
Grip	0.330	1.899	0.0136
Club	0.780	0.292	0.0257

The mass of the shoulder link is not required because this link is pivoted at its center of mass and has no translational motion.

Results and Discussion

Figure 3 shows the club head speed during the downswing for different switching times of the wrist torque. It can be observed that for $t_w = 0.15$ s, the speed reaches its maximum before impact — this leads to early hitting. On the other hand, for $t_w = 0.23$ s, the club head speed could not even reach its maximum at the time of impact.

For $t_w = 0.19$ s, the club head speed is higher than the other two cases and close to the optimum value for the chosen geometrical parameters and muscle strength.

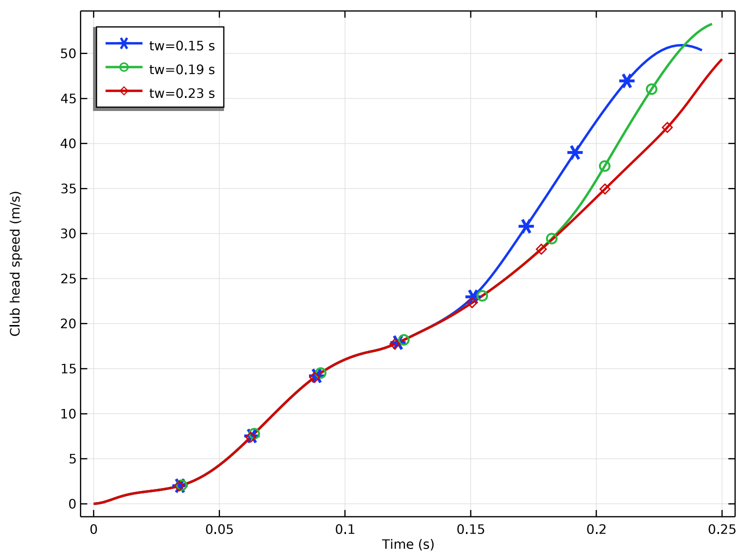

Figure 3: Club head speed during the downswing for different switching times of the wrist torque.

The driving torques, applied by the shoulder, arm, and the wrist are shown in Figure 4. The applied shoulder torque is assumed to start at its maximum positive value, after a short build-up time. The applied arm torque, which acts on the arm and reacts on the shoulder, increases linearly with time to its maximum positive value with a specified rate. The applied wrist torque, which acts on the club and reacts on the arm, is fully negative to start and switches to its maximum positive value at the specified time. The instance, when wrist torque switches to its maximum positive value, is the crucial parameter and hence its effect is studied in this analysis.

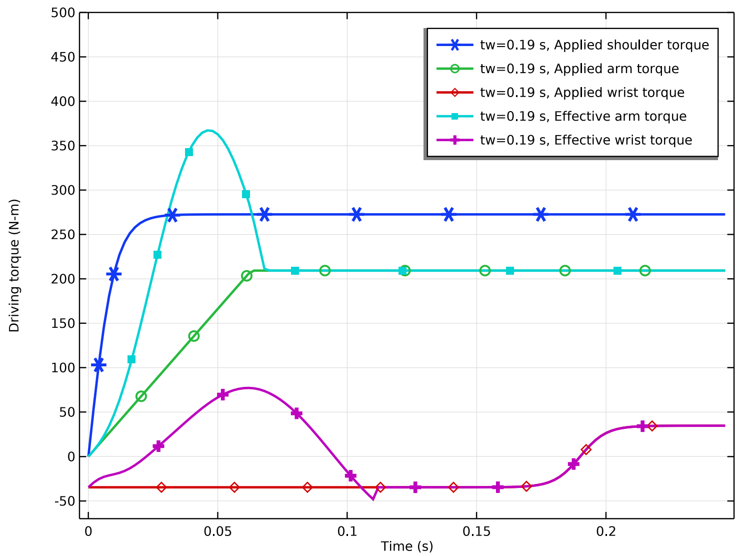

Figure 4: Time history of torque applied by the shoulder, arm, and wrist.

On the arm and wrist joint, the rotation is not fully free. It is limited in the forward and backward directions by the ligaments, muscles, joint shape, or a combination of all these. In our golf-swing analysis, the rotation limit in the backward direction is more important and this limiting value may vary from person to person.

In the beginning of the downswing, various parts try to rotate beyond their limiting values due to inertial forces. This is resisted by the stop which is modeled using the spring and damper on joints. The resistive moment applied by the stop changes the effective torque in the arm and the wrist as shown in Figure 4.

Figure 5 shows the relative rotation on the arm, wrist, and the shaft joints for $t_w = 0.19$ s. It can be seen that during the downswing, the arm rotates with respect to the shoulder by approximately 20°. The wrist joint has the maximum rotation and the club (or the grip) rotates with respect to the arm by approximately 85°. The shaft joint has very little rotation compared to the wrist and the arm joint. Hence it can be said that, for the chosen values of stiffness and damping, the effect of shaft flexibility to the swing is negligible compared to other parameters.

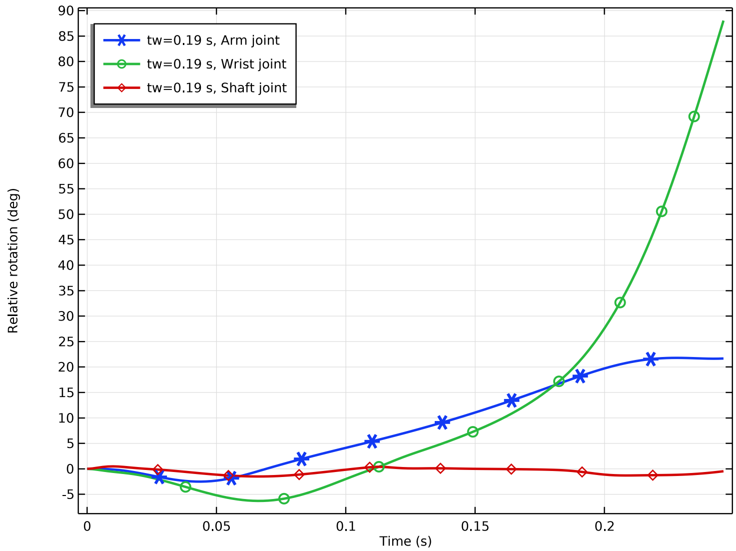

Figure 5: Rotations on the arm, wrist, and the shaft joints.

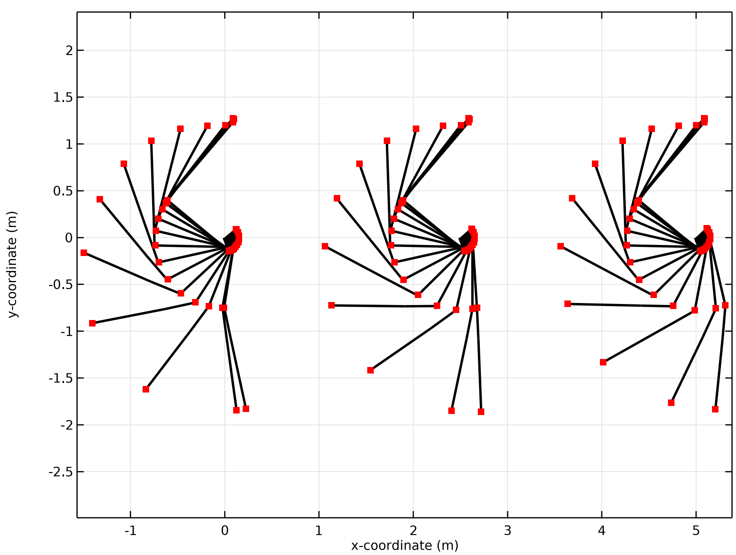

Figure 6: Golf club trajectory for different values of wrist torque switch time. From left to right, results are displayed for the increasing values of the parameter.

OUTCOME OF THE ANALYSIS

Maximum arm torque throughout the swing and very high arm speed in the beginning of the downswing can cause an early release, with the club head reaching its maximum speed before actually hitting the ball.

It can also be deduced that for the given torque capacity, it is potentially advantageous to have a long arm swing as well as a large wrist-cock limit angle. Furthermore, the extent to which the wrist can hold back the release is limited by its torque capacity. Therefore, your golfing skills are also strongly associated with the delayed release and the late hit.

Notes About the COMSOL Implementation

- In this model, linkages are modeled as rigid elements using **Rigid Material** nodes as we are only interested in the kinematics of the mechanism. Linkages can be modeled as flexible elements using the **Linear Elastic Material** node if the stresses and deformations in the linkages are also of interest.
- The **Mass and Moment of Inertia** subnode of the **Rigid Material** node is used to enter the inertia properties given at a certain point.
- The connections set up in the model can be reviewed in the **Joints Summary** section at the physics node.

Reference

1. R.S. Sharp, "On the Mechanics of the Golf Swing," *Proc. the Royal Society A*, vol. 465, pp. 551–570, 2009.

Application Library path: `Multibody_Dynamics_Module/Biomechanics/golf_swing_mechanics`

Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **2D**.
2 In the **Select Physics** tree, select **Structural Mechanics > Multibody Dynamics (mbd)**.
3 Click **Add**.
4 Click **Study**.
5 In the **Select Study** tree, select **General Studies > Time Dependent**.
6 Click **Done**.

GLOBAL DEFINITIONS

Import the parameter list defining the mass and inertia properties of the linkages, joint stiffness, and maximum torque capacities.

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.
2 In the **Settings** window for **Parameters**, locate the **Parameters** section.
3 Click **Load from File**.
4 Browse to the model's Application Libraries folder and double-click the file `golf_swing_mechanics_parameters.txt`.

GEOMETRY 1

Import 1 (imp1)

1 In the **Home** toolbar, click **Import**.
2 In the **Settings** window for **Import**, locate the **Source** section.
3 Click **Browse**.
4 Browse to the model's Application Libraries folder and double-click the file `golf_swing_mechanics.mphbin`.
5 Click **Import**.

Form Union (fin)

1 In the **Model Builder** window, under **Component 1 (comp1) > Geometry 1** click **Form Union (fin)**.
2 In the **Settings** window for **Form Union/Assembly**, locate the **Form Union/Assembly** section.
3 From the **Action** list, choose **Form an assembly**.
4 Clear the **Create pairs** checkbox.
5 In the **Home** toolbar, click **Build All**.

DEFINITIONS

Integration 1 (intop1)

1. In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.
2. In the **Settings** window for **Integration**, locate the **Source Selection** section.
3. From the **Geometric entity level** list, choose **Point**.
4. Select Point 14 only.

Variables 1

1. In the **Model Builder** window, right-click **Definitions** and choose **Variables**.

   Import the expressions for the torque applied by different body parts.
2. In the **Settings** window for **Variables**, locate the **Variables** section.
3. Click **Load from File**.
4. Browse to the model's Application Libraries folder and double-click the file `golf_swing_mechanics_variables.txt`.

MULTIBODY DYNAMICS (MBD)

Rigid Material: Shoulder

1. In the **Physics** toolbar, click **Domains** and choose **Rigid Material**.
2. In the **Settings** window for **Rigid Material**, type `Rigid Material: Shoulder` in the **Label** text field.
3. Select Domain 4 only.

   Set the density to zero and use the **Mass and Moment of Inertia** subnode to add lumped mass and moment of inertia values.
4. Locate the **Density** section. From the ρ list, choose **User defined**.

Mass and Moment of Inertia 1

1. In the **Physics** toolbar, click **Attributes** and choose **Mass and Moment of Inertia**.
2. In the **Settings** window for **Mass and Moment of Inertia**, locate the **Mass and Moment of Inertia** section.
3. In the I_z text field, type `Ish`.

Rigid Material: Arm

1. In the **Physics** toolbar, click **Domains** and choose **Rigid Material**.
2. In the **Settings** window for **Rigid Material**, type `Rigid Material: Arm` in the **Label** text field.

3 Select Domain 2 only.

4 Locate the **Density** section. From the ρ list, choose **User defined**.

Mass and Moment of Inertia 1

1 In the **Physics** toolbar, click **Attributes** and choose **Mass and Moment of Inertia**.

2 In the **Settings** window for **Mass and Moment of Inertia**, locate the **Center of Mass** section.

3 From the list, choose **Centroid of selected entities**.

4 From the **Entity level** list, choose **Point**.

5 Locate the **Mass and Moment of Inertia** section. In the m text field, type `Ma`.

6 In the I_z text field, type `Ia`.

Center of Mass: Point 1

1 In the **Model Builder** window, click **Center of Mass: Point 1**.

2 Select Point 8 only.

Rigid Material: Grip

1 In the **Physics** toolbar, click **Domains** and choose **Rigid Material**.

2 In the **Settings** window for **Rigid Material**, type `Rigid Material: Grip` in the **Label** text field.

3 Select Domain 1 only.

4 Locate the **Density** section. From the ρ list, choose **User defined**.

Mass and Moment of Inertia 1

1 In the **Physics** toolbar, click **Attributes** and choose **Mass and Moment of Inertia**.

2 In the **Settings** window for **Mass and Moment of Inertia**, locate the **Center of Mass** section.

3 From the list, choose **Centroid of selected entities**.

4 From the **Entity level** list, choose **Point**.

5 Locate the **Mass and Moment of Inertia** section. In the m text field, type `Mg`.

6 In the I_z text field, type `Ig`.

Center of Mass: Point 1

1 In the **Model Builder** window, click **Center of Mass: Point 1**.

2 Select Point 3 only.

Rigid Material: Club

1 In the **Physics** toolbar, click **Domains** and choose **Rigid Material**.

2 In the **Settings** window for **Rigid Material**, type `Rigid Material: Club` in the **Label** text field.

3 Select Domain 3 only.

4 Locate the **Density** section. From the ρ list, choose **User defined**.

Mass and Moment of Inertia 1

1 In the **Physics** toolbar, click **Attributes** and choose **Mass and Moment of Inertia**.

2 In the **Settings** window for **Mass and Moment of Inertia**, locate the **Center of Mass** section.

3 From the list, choose **Centroid of selected entities**.

4 From the **Entity level** list, choose **Point**.

5 Locate the **Mass and Moment of Inertia** section. In the m text field, type `Mc`.

6 In the I_z text field, type `Ic`.

Center of Mass: Point 1

1 In the **Model Builder** window, click **Center of Mass: Point 1**.

2 Select Point 13 only.

Rigid Material: Arm, Rigid Material: Club, Rigid Material: Grip, Rigid Material: Shoulder

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Multibody Dynamics (mbd)**, Ctrl-click to select **Rigid Material: Shoulder**, **Rigid Material: Arm**, **Rigid Material: Grip**, and **Rigid Material: Club**.

2 Right-click and choose **Group**.

Rigid Materials

In the **Settings** window for **Group**, type `Rigid Materials` in the **Label** text field.

Hinge Joint: Shoulder

1 In the **Physics** toolbar, click **Global** and choose **Hinge Joint**.

2 In the **Settings** window for **Hinge Joint**, type `Hinge Joint: Shoulder` in the **Label** text field.

3 Locate the **Attachment Selection** section. From the **Source** list, choose **Fixed**.

4 From the **Destination** list, choose **Rigid Material: Shoulder**.

Center of Joint: Boundary 1

1 In the **Model Builder** window, click **Center of Joint: Boundary 1**.

2 Select Boundary 13 only.

Hinge Joint: Shoulder

In the **Model Builder** window, click **Hinge Joint: Shoulder**.

Applied Force and Moment 1

1 In the **Physics** toolbar, click **Attributes** and choose **Applied Force and Moment**.

2 In the **Settings** window for **Applied Force and Moment**, locate the **Applied On** section.

3 From the list, choose **Joint**.

4 Locate the **Applied Force and Moment** section. In the M text field, type `Tsh`.

Hinge Joint: Arm

1 In the **Physics** toolbar, click **Global** and choose **Hinge Joint**.

2 In the **Settings** window for **Hinge Joint**, type `Hinge Joint: Arm` in the **Label** text field.

3 Locate the **Attachment Selection** section. From the **Source** list, choose **Rigid Material: Shoulder**.

4 From the **Destination** list, choose **Rigid Material: Arm**.

Center of Joint: Boundary 1

1 In the **Model Builder** window, click **Center of Joint: Boundary 1**.

2 Select Boundary 8 only.

Hinge Joint: Arm

In the **Model Builder** window, click **Hinge Joint: Arm**.

Spring and Damper 1

1 In the **Physics** toolbar, click **Attributes** and choose **Spring and Damper**.

2 In the **Settings** window for **Spring and Damper**, locate the **Spring and Damper: Rotational** section.

3 In the k_θ text field, type `ka*(mbd.hgj2.th<0)`.

4 In the c_θ text field, type `ca*(mbd.hgj2.th<0)`.

Hinge Joint: Arm

In the **Model Builder** window, click **Hinge Joint: Arm**.

Applied Force and Moment 1

1 In the **Physics** toolbar, click **Attributes** and choose **Applied Force and Moment**.

2 In the **Settings** window for **Applied Force and Moment**, locate the **Applied On** section.

3 From the list, choose **Joint**.

4 Locate the **Applied Force and Moment** section. In the M text field, type `Ta`.

Hinge Joint: Wrist

1 In the **Physics** toolbar, click **Global** and choose **Hinge Joint**.

2 In the **Settings** window for **Hinge Joint**, type `Hinge Joint: Wrist` in the **Label** text field.

3 Locate the **Attachment Selection** section. From the **Source** list, choose **Rigid Material: Arm**.

4 From the **Destination** list, choose **Rigid Material: Grip**.

Center of Joint: Boundary 1

1 In the **Model Builder** window, click **Center of Joint: Boundary 1**.

2 Select Boundary 1 only.

Hinge Joint: Wrist

In the **Model Builder** window, click **Hinge Joint: Wrist**.

Spring and Damper 1

1 In the **Physics** toolbar, click **Attributes** and choose **Spring and Damper**.

2 In the **Settings** window for **Spring and Damper**, locate the **Spring and Damper: Rotational** section.

3 In the k_θ text field, type `kw*(mbd.hgj3.th<0)`.

4 In the c_θ text field, type `cw*(mbd.hgj3.th<0)`.

Hinge Joint: Wrist

In the **Model Builder** window, click **Hinge Joint: Wrist**.

Applied Force and Moment 1

1 In the **Physics** toolbar, click **Attributes** and choose **Applied Force and Moment**.

2 In the **Settings** window for **Applied Force and Moment**, locate the **Applied On** section.

3 From the list, choose **Joint**.

4 Locate the **Applied Force and Moment** section. In the M text field, type `Tw`.

Hinge Joint: Shaft

1 In the **Physics** toolbar, click **Global** and choose **Hinge Joint**.

2 In the **Settings** window for **Hinge Joint**, type `Hinge Joint: Shaft` in the **Label** text field.

3 Locate the **Attachment Selection** section. From the **Source** list, choose **Rigid Material: Grip**.

4 From the **Destination** list, choose **Rigid Material: Club**.

Center of Joint: Boundary 1

1 In the **Model Builder** window, click **Center of Joint: Boundary 1**.

2 Select Boundary 9 only.

Hinge Joint: Shaft

In the **Model Builder** window, click **Hinge Joint: Shaft**.

Spring and Damper 1

1 In the **Physics** toolbar, click **Attributes** and choose **Spring and Damper**.

2 In the **Settings** window for **Spring and Damper**, locate the **Spring and Damper: Rotational** section.

3 In the k_θ text field, type `ks`.

4 In the c_θ text field, type `cs`.

Hinge Joint: Arm, Hinge Joint: Shaft, Hinge Joint: Shoulder, Hinge Joint: Wrist

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Multibody Dynamics (mbd)**, Ctrl-click to select **Hinge Joint: Shoulder**, **Hinge Joint: Arm**, **Hinge Joint: Wrist**, and **Hinge Joint: Shaft**.

2 Right-click and choose **Group**.

Hinge Joints

In the **Settings** window for **Group**, type `Hinge Joints` in the **Label** text field.

DEFINITIONS

Variables 1

Add a few more variables to use them in the postprocessing.

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Definitions** click **Variables 1**.

2 In the **Settings** window for **Variables**, locate the **Variables** section.

3 In the table, enter the following settings:

Name	Expression	Unit	Description
Ta_eff	Ta-mbd.hgj2.sd1.Ms-mbd.hgj2.sd1.Md		Effective arm torque
Tw_eff	Tw-mbd.hgj3.sd1.Ms-mbd.hgj3.sd1.Md		Effective wrist torque

STUDY 1

Add a **Parametric Sweep** to solve the model for different values of wrist torque switch time.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
tw (Wrist torque switch time)	`0.15 0.19 0.23`	s

Step 1: Time Dependent

1 In the **Model Builder** window, click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

3 In the **Output times** text field, type `range(0,2e-3,0.26)`.

Add a **Stop Condition** in the solver in order to stop the simulation just prior to the impact with the ball.

Solution 1 (sol1)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 1 (sol1)** node.

3 Right-click **Study 1 > Solver Configurations > Solution 1 (sol1) > Time-Dependent Solver 1** and choose **Stop Condition**.

4 In the **Settings** window for **Stop Condition**, locate the **Stop Expressions** section.

5 Click **Add**.

6 In the table, enter the following settings:

Stop expression	Stop if	Active	Description
`comp1.stop`	True (>=1)	√	`Stop expression 1`

7 Locate the **Output at Stop** section. From the **Add solution** list, choose **Step after stop**.

8 In the **Study** toolbar, click **Compute**.

RESULTS

Follow the instructions below to add the point trajectory plot.

Displacement (mbd)

In the **Model Builder** window, under **Results** click **Displacement (mbd)**.

Point Trajectories 1

1 In the **Displacement (mbd)** toolbar, click **More Plots** and choose **Point Trajectories**.

2 Select Points 1, 9, and 14 only.

3 In the **Settings** window for **Point Trajectories**, locate the **Coloring and Style** section.

4 Find the **Line style** subsection. From the **Type** list, choose **Tube**.

Color Expression 1

1 Right-click **Point Trajectories 1** and choose **Color Expression**.

2 In the **Settings** window for **Color Expression**, locate the **Expression** section.

3 In the **Expression** text field, type `t`.

4 Locate the **Coloring and Style** section. Clear the **Color legend** checkbox.

5 In the **Displacement (mbd)** toolbar, click **Plot**.

6 Click the **Zoom Extents** button in the **Graphics** toolbar.

Follow the instructions below to generate the plot of club head speed shown in Figure 3.

Club Head Speed

1 In the **Results** toolbar, click **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Club Head Speed` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol2)**.

4 Click to expand the **Title** section. From the **Title type** list, choose **None**.

5 Locate the **Plot Settings** section.

6 Select the **y-axis label** checkbox. In the associated text field, type `Club head speed (m/s)`.

7 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

Point Graph 1

1 Right-click **Club Head Speed** and choose **Point Graph**.

2 Select Point 14 only.

3 In the **Settings** window for **Point Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Multibody Dynamics** > **Acceleration and velocity** > **mbd.vel - Velocity magnitude - m/s**.

4 Click to expand the **Coloring and Style** section. From the **Width** list, choose **2**.

5 Find the **Line markers** subsection. From the **Marker** list, choose **Cycle**.

6 From the **Positioning** list, choose **Interpolated**.

7 Click to expand the **Legends** section. Select the **Show legends** checkbox.

8 From the **Legends** list, choose **Evaluated**.

9 In the **Legend** text field, type `tw=eval(tw,s) s`.

10 In the **Club Head Speed** toolbar, click **Plot**.

11 Click the **Zoom Extents** button in the **Graphics** toolbar.

Follow the instructions below to generate the plot of driving torques as shown in Figure 4.

Driving Torques

1. In the **Results** toolbar, click **1D Plot Group**.
2. In the **Settings** window for **1D Plot Group**, type `Driving Torques` in the **Label** text field.
3. Locate the **Data** section. From the **Dataset** list, choose **Study 1/ Parametric Solutions 1 (sol2)**.
4. From the **Parameter selection (tw)** list, choose **From list**.
5. In the **Parameter values (tw (s))** list box, select **0.19**.
6. Locate the **Title** section. From the **Title type** list, choose **None**.
7. Locate the **Plot Settings** section.
8. Select the **y-axis label** checkbox. In the associated text field, type `Driving torque (N-m)`.

Global 1

1. Right-click **Driving Torques** and choose **Global**.
2. In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Definitions** > **Variables** > **Tsh - Applied shoulder torque - N·m**.
3. Click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Definitions** > **Variables** > **Ta - Applied arm torque - N·m**.
4. Click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Definitions** > **Variables** > **Tw - Applied wrist torque - N·m**.
5. Click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Definitions** > **Variables** > **Ta_eff - Effective arm torque - N·m**.
6. Click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Definitions** > **Variables** > **Tw_eff - Effective wrist torque - N·m**.
7. Click to expand the **Coloring and Style** section. From the **Width** list, choose **2**.
8. Find the **Line markers** subsection. From the **Marker** list, choose **Cycle**.
9. From the **Positioning** list, choose **Interpolated**.

Driving Torques

1 In the **Model Builder** window, click **Driving Torques**.

2 In the **Settings** window for **1D Plot Group**, locate the **Axis** section.

3 Select the **Manual axis limits** checkbox.

4 In the **y minimum** text field, type -70.

5 In the **y maximum** text field, type 500.

6 In the **Driving Torques** toolbar, click **Plot**.

Follow the instructions below to plot the relative rotation at the joints as shown in Figure 5.

Relative Rotation

1 Right-click **Driving Torques** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Relative Rotation` in the **Label** text field.

3 Locate the **Plot Settings** section. In the **y-axis label** text field, type `Relative rotation (deg)`.

4 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

Global 1

1 In the **Model Builder** window, expand the **Relative Rotation** node, then click **Global 1**.

2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Multibody Dynamics** > **Hinge joints** > **Hinge Joint: Arm** > **mbd.hgj2.th - Relative rotation - rad**.

3 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
mbd.hgj2.th	deg	Arm joint

4 Click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Multibody Dynamics** > **Hinge joints** > **Hinge Joint: Wrist** > **mbd.hgj3.th - Relative rotation - rad**.

5 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
mbd.hgj3.th	deg	Wrist joint

6 Click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Multibody Dynamics** > **Hinge joints** > **Hinge Joint: Shaft** > **mbd.hgj4.th - Relative rotation - rad**.

7 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
mbd.hgj4.th	deg	Shaft joint

8 In the **Relative Rotation** toolbar, click **Plot**.

9 Click the **Zoom Extents** button in the **Graphics** toolbar.

Follow the steps below to plot the trajectory of shoulder-arm-club motion as shown in Figure 6.

Shoulder-arm-club Motion

1 In the **Results** toolbar, click **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Shoulder-arm-club Motion` in the **Label** text field.

Line Graph 1

1 Right-click **Shoulder-arm-club Motion** and choose **Line Graph**.

2 In the **Settings** window for **Line Graph**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 1/Parametric Solutions 1 (sol2)**.

4 From the **Parameter selection (tw)** list, choose **From list**.

5 In the **Parameter values (tw (s))** list box, select **0.15**.

6 From the **Time selection** list, choose **Interpolated**.

7 In the **Times (s)** text field, type `range(0,2e-2,0.26)`.

8 Locate the **Selection** section. Click **Paste Selection**.

9 In the **Paste Selection** dialog, type `2 6 10 14` in the **Selection** text field.

10 Click **OK**.

11 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.

12 In the **Expression** text field, type `y`.

13 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

14 In the **Expression** text field, type `x`.

15 Click to expand the **Coloring and Style** section. From the **Color** list, choose **Black**.

16 From the **Width** list, choose **2**.

Point Graph 1

1 In the **Model Builder** window, right-click **Shoulder-arm-club Motion** and choose **Point Graph**.

2 In the **Settings** window for **Point Graph**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 1/Parametric Solutions 1 (sol2)**.

4 From the **Parameter selection (tw)** list, choose **From list**.

5 In the **Parameter values (tw (s))** list box, select **0.15**.

6 From the **Time selection** list, choose **Interpolated**.

7 In the **Times (s)** text field, type `range(0,2e-2,0.26)`.

8 Locate the **Selection** section. Click **Paste Selection**.

9 In the **Paste Selection** dialog, type `6 14 18` in the **Selection** text field.

10 Click **OK**.

11 In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.

12 In the **Expression** text field, type `y`.

13 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

14 In the **Expression** text field, type `x`.

15 Locate the **Coloring and Style** section. From the **Color** list, choose **Red**.

16 Find the **Line style** subsection. From the **Line** list, choose **None**.

17 Find the **Line markers** subsection. From the **Marker** list, choose **Point**.

Line Graph 2

1 In the **Model Builder** window, under **Results** > **Shoulder-arm-club Motion** right-click **Line Graph 1** and choose **Duplicate**.

2 In the **Settings** window for **Line Graph**, locate the **Data** section.

3 In the **Parameter values (tw (s))** list box, select **0.19**.

4 Locate the **x-Axis Data** section. In the **Expression** text field, type `x+2.5`.

Point Graph 2

1 In the **Model Builder** window, under **Results** > **Shoulder-arm-club Motion** right-click **Point Graph 1** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, locate the **Data** section.

3 In the **Parameter values (tw (s))** list box, select **0.19**.

4 Locate the **x-Axis Data** section. In the **Expression** text field, type `x+2.5`.

Line Graph 3

1 In the **Model Builder** window, under **Results** > **Shoulder-arm-club Motion** right-click **Line Graph 2** and choose **Duplicate**.

2 In the **Settings** window for **Line Graph**, locate the **Data** section.

3 In the **Parameter values (tw (s))** list box, select **0.23**.

4 Locate the **x-Axis Data** section. In the **Expression** text field, type `x+5`.

Point Graph 3

1 In the **Model Builder** window, under **Results** > **Shoulder-arm-club Motion** right-click **Point Graph 2** and choose **Duplicate**.

2 In the **Settings** window for **Point Graph**, locate the **Data** section.

3 In the **Parameter values (tw (s))** list box, select **0.23**.

4 Locate the **x-Axis Data** section. In the **Expression** text field, type `x+5`.

5 In the **Shoulder-arm-club Motion** toolbar, click **Plot**.

6 Click the **Zoom Extents** button in the **Graphics** toolbar.

Shoulder-arm-club Motion

1 In the **Model Builder** window, click **Shoulder-arm-club Motion**.

2 In the **Settings** window for **1D Plot Group**, locate the **Title** section.

3 From the **Title type** list, choose **None**.

4 Locate the **Plot Settings** section.

5 Select the **x-axis label** checkbox. In the associated text field, type `x-coordinate (m)`.

6 Locate the **Axis** section. Select the **Preserve aspect ratio** checkbox.

7 In the **Shoulder-arm-club Motion** toolbar, click **Plot**.

8 Click the **Zoom Extents** button in the **Graphics** toolbar.

Finally, you can generate an animation of the shoulder-arm-club motion together with the trajectory of joints and club head for different values of wrist torque switch time.