**Guidance on Using OpenSim Simulation on Ankle Inversions**

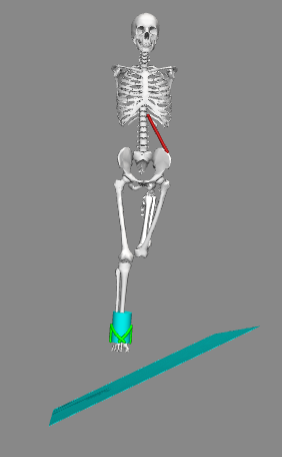
***Zehao’s***

1. **Simulation through GUI of OpenSim**
   1. **Drop Landing Simulation**

The purpose of the drop landing simulation in OpenSim is to predict the risk of ankle inversion injury by free landing onto an inclined plate under different conditions which include: wearing an ankle foot orthosis (AFO) or not wearing an AFO as well as the height and angle of the landing platform.

* + 1. **GUI of Drop Landing Simulation**

Open the file in OpenSim software GUI, the drop landing system is shown which consists of musculoskeletal model, ankle foot orthosis and landing platform.



Musculoskeletal Model

Landing Platform

Ankle Foot Orthosis

**Figure 1:** Illustration of drop landing model consisting of musculoskeletal model, ankle foot orthosis and landing platform

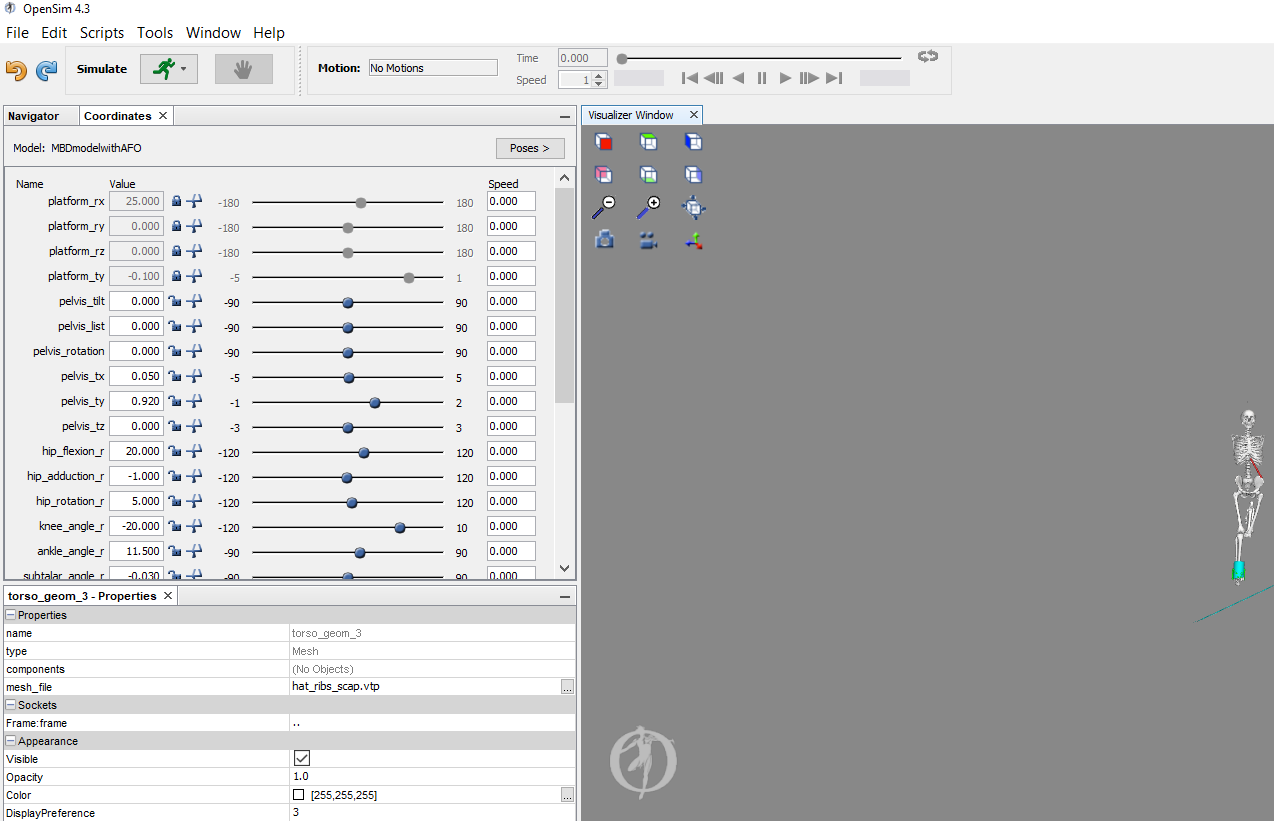
All of these three conditions can be adjusted in the software in order to predict the ankle inversion during a drop landing in different situations.

**Explore the Musculoskeletal Model**

The musculoskeletal model used in Drop Landing Simulation has a torso, a pelvis and two legs with a total of 23 degrees of freedom and 70 muscle-tendon actuators. Various components of the model can be explored using the **Navigator** panel including **Bodies** and **Joints**. To evaluate the level of ankle inversion, motion between the tibia and right foot is focussed which is associated with the subtalar joint in the ankle. The subtalar joint of right ankle can be found as **subtalar\_r** in the **Joints** group in the Navigator panel.

**Landing Platform**

The height of drop and inclined angle of landing platform will influence the level of ankle inversion. These can be adjusted in the **Coordinates** tab in the GUI where **platform\_rx** represents the pre-defined slope angle of the landing platform and drop height can be worked out by calculating the difference between **pelvis\_ty** (pre-defined height of musculoskeletal model) and **platform\_ty** (pre-defined height of the landing platform). The angle and position of other sections in the musculoskeletal model such as knee or hip can also be adjusted in the ‘Coordinate’ tab if needed.

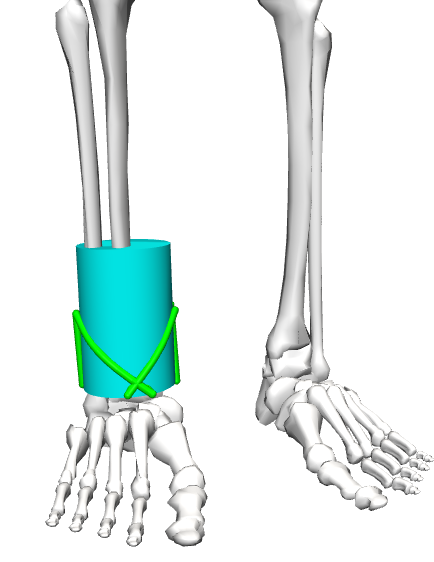
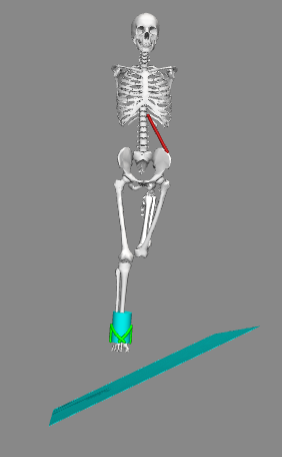


Coordinate Tab

**Figure 2:** Illustration of Coordinate Tab in OpenSim software GUI

**Ankle Foot Orthosis**

An ankle foot orthosis (AFO) is added on the right foot ankle of the musculoskeletal model in order to evaluate the effect of wearing an ankle foot orthosis to ankle inversion in drop landing. In this example, the AFO design is constructed with four straps which is simulated to the AFO prototype utilized in real life experiments. A cylinder (in green colour as shown in Figure 3) is also developed to represent human leg and the AFO straps are wrapped around the cylinder in the model.



Strap 1

Strap 2

Strap 3

Strap 4



**AFO Prototype**

**AFO Design in Simulation**

Cylinder that represents human leg

**Figure 3:** Illustration of AFO design used in the drop landing model which consists of four straps and the actual AFO prototype utilized in experiments

Text, letter

Description automatically generatedThe four straps of AFO, Strap 1, Strap 2, Strap 3 and Strap 4, were simulated as ligaments in the OpenSim model, and can be found as **orthosis\_1**, **orthosis\_2**, **orthosis\_3** and **orthosis\_4** in the Navigator tab respectively. To fully evaluate the influence of different AFO designs on the ankle joint motion during drop landing simulation, various design variables of AFO can be changed in the OpenSim model including: mechanical properties of each AFO strap as well as number, orientations and locations of AFO straps. All of these design variables can be varied through modifying the parameters in the **AFO input text file**.

**Figure 4:** Design variables of Ankle Foot Orthosis model in the AFO input text file.

Number, Orientation and Location of AFO Straps

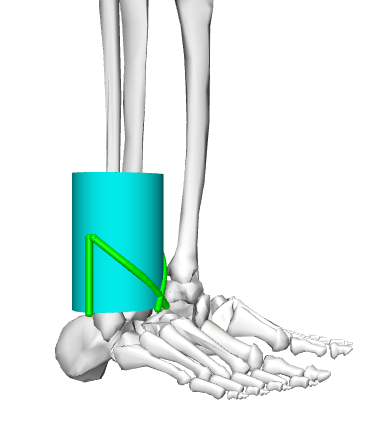
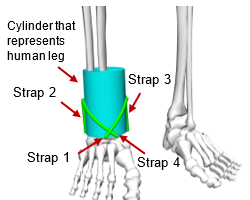
A picture containing text

Description automatically generatedThe number of straps of the AFO model can be varied through changing the AFO text input file. In this example, a total of four straps is utilized and each strap is numbered. The design variables related to the orientation and location of AFO straps are highlighted in the image below.

**Figure 5:** Design variables included in the red rectangle are utilized to vary the orientation and location of AFO straps

**AFO\_bottom\_location** defines the origin coordinate of AFO model and the location and orientation of other AFO straps will use this coordinate as reference.

**AFO\_cylinder\_radius** defines the radius of cylinder which represents to the human leg.



Strap 2

**Figure 6:** Representation of orientation and location of four AFO straps

**AFO\_height** defines the length of AFO straps that are placed vertically, such as Strap 2 and Strap 3 in this example.

**AFO\_bottom\_location\_angle** is utilized to define the bottom location of each AFO strap by setting the angle between the x-axis (global coordinate axes of the musculoskeletal model) and the bottom point of the AFO strap. In this example, the four elements in the AFO\_bottom\_location\_angle list represent the angle of bottom location of AFO Strap 1, Strap 2, Strap 3 and Strap 4, respectively. An example is illustrated in Figure 7 where point O is the origin point, point B is the bottom location point of an AFO strap, the bottom location angle of this AFO strap is defined as , and r is the pre-defined radius of the cylinder (human leg). Afterwards, the coordinate of point B in the global coordinate system can be calculated.



**Figure 7:**  Schematical example showing how to define the bottom location of AFO straps in OpenSim

**AFO\_Strap\_Orientations** is adopted to define the orientation angle of an AFO strap compared to z-axis (vertical axis) in the global coordinate system of the model. Similarly, the AFO\_Strap\_Orientations list has four elements in this example which represent the orientation angle of Strap 1, Strap 2, Strap 3 and Strap 4, respectively. Because the Strap 2 and 3 are placed vertically in the current example, their orientation angle is . While Strap 1 and 4 are designed to cross each other, and thus they have an orientation angle of and , respectively. A visual example is given in Figure 8 where the line connecting point B and T representing Strap 4 of the AFO. The orientation angle of this AFO strap is defined as in the diagram. Afterwards, both the coordinate of point T and actual length of Strap 4 can also be calculated.



Height of AFO



B

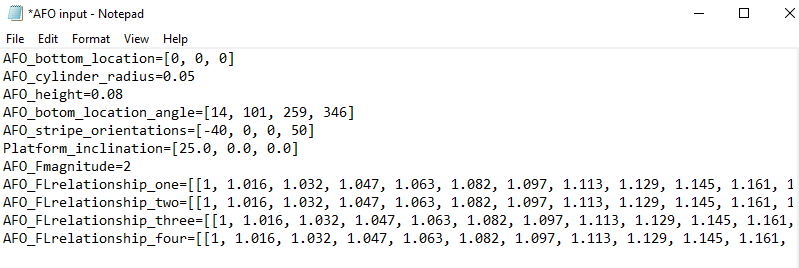
T

**Figure 8:** Diagram presenting the orientation angle of AFO Strap 4 and calculations of its length in this example

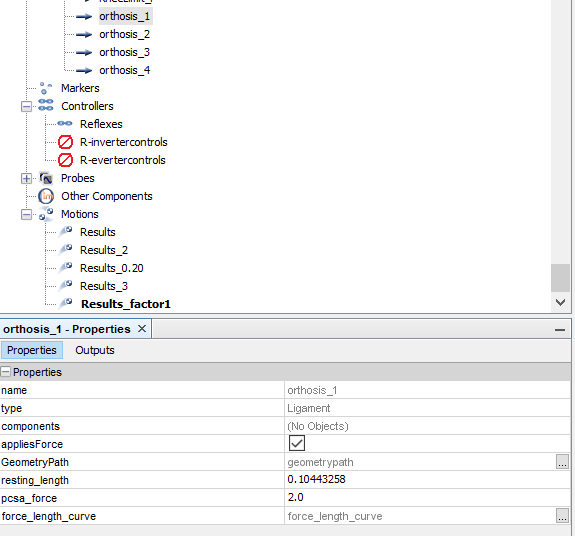
**Platform\_inclination** apart from setting in OpenSim software GUI, the incline angle of landing platform can also be set in the AFO Input text file.

Mechanical Properties of each AFO Strap

Design variables utilized to adjust the mechanical properties of each AFO strap are presented in Figure 9. These variables can also be defined in the OpenSim software GUI by finding the particular AFO strap in the Navigation tab (Figure 10).



**Figure 9:** Design variables included in the red rectangle are utilized to vary the mechanical properties of AFO straps



Select the AFO Strap being defined

Length of the AFO Strap

Mechanical Properties of the AFO Strap

**Figure 10:** Diagram showing how to adjust the design variables for defining mechanical properties of AFO Strap 1

**AFO\_Fmagnitude** is an amplification factor used for amplifying the force provided by AFO straps. This factor can also be defined in the OpenSim software GUI as **psca\_force** as shown in Figure 10.

**AFO\_Flrelationship** is utilized to define the force\_length relationship of the AFO Strap. The input force\_length relationship curve is according to actual mechanical behaviour of material utilized for the AFO strap. The x-axis of the curve is calculated as dividing the length of AFO strap after extension by the original length of the strap,

where is the original length of the AFO strap, is length of the strap after extension. While y-axis of the curve is the force exhibited by the AFO strap at different extension length. The x-axis and y-axis values of the force\_length relationship curve can be input by either AFO Input text file shown in Figure 10 or OpenSim software GUI, and the input curve can be viewed in the GUI (Figure 11).

Chart, line chart

Description automatically generated

**Figure 11:** Input Force\_length relationship curve of AFO Strap 1

**1.2.1 Perform the Drop Landing Simulation**

After all the above parameters are set, drop landing simulation can be performed in the OpenSim GUI by clicking the simulate button (Figure 12). The time period of simulation can be defined as well.

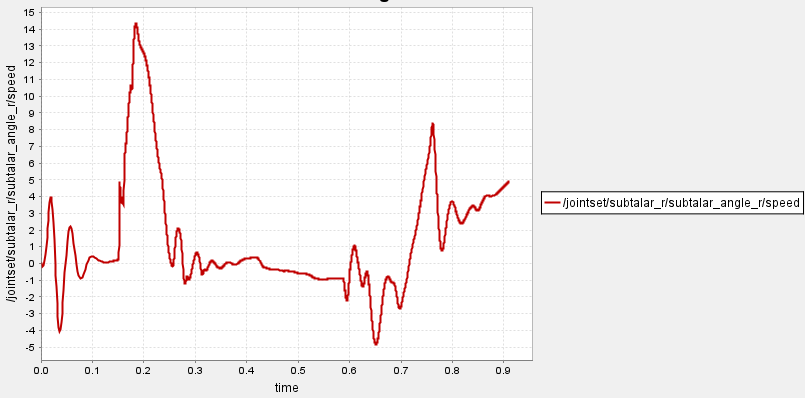
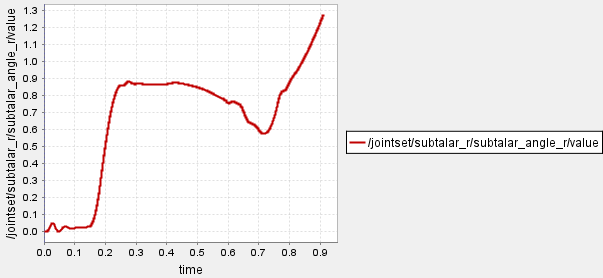
Graphical user interface, application, Word

Description automatically generated

**Figure 12:** Simulate button to perform the drop landing simulation

**1.2.2 Plot the Simulation Results**

To plot the simulation results, a new plot window can be opened by selecting **Tools>Plot** in the OpenSim GUI. Afterwards, click the **Y-Quantity**  button and select **Load file** to select the set of result being plot. In the **Filter by pattern** text box, search for the results wanted to be plot. For evaluating the level of ankle inversion, **subtalar\_angle\_r/value** (radians)and **subtalar\_angle\_r/speed** (radians/second)**,** representing the rotation angle and angular speed of subtalar joint of right foot ankle during drop landing simulation, are selected to plot. For the x-axis, click the **X-Quantity** button and choose time. Afterwards, plots illustrating rotation angle of subtalar joint against time and angular speed of subtalar joint against time during drop landing simulation can be generated. Examples of these plots are shown in Figure 13.



**(a)**

**(b)**

**Figure 13:** Examples of (a) Rotation angle of subtalar joint against time (b) Angular speed of subtalar joint against time during drop landing

Typically, for evaluating the motion of ankle inversion during drop landing, only the results within the beginning 0.25 second of simulation is analysed.

***Xijin Hua’s***

**The representation of AFO in the musculoskeletal model**

The 3D printed AFO will be represented as several nonlinear straps, modelling as ligament elements in the musculoskeletal (MSK) model, as shown in Figure 1:



Figure 1: The 3D printed AFO in the musculoskeletal model was represented as several straps

1. ***The locations and geometries of the AFO representation***

The location of the AFO strap in the MSK model, the size and nonlinear mechanical properties of the straps were determined using a series of design variables, which were summarized in a text file (e.g. AFO input.txt), as shown in Figure 2. The AFO representation in the MSK model was then generated based on these design variables. The details about how to generate the AFO representation will be detailed below.

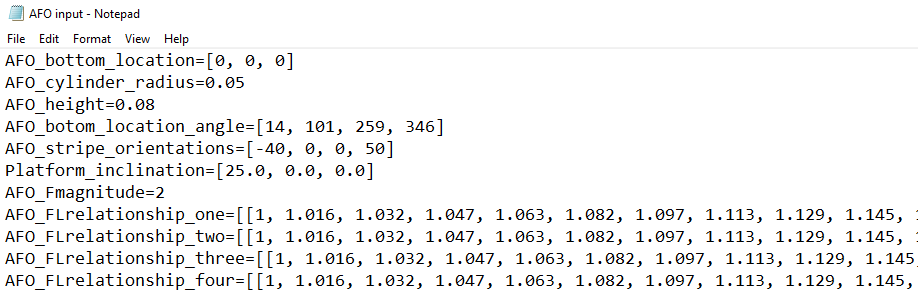


Figure 2: the design variables for the AFO representation in the MSK model

***AFO\_bottom\_location:*** this variable defines the location of the centre of the AFO bottom relative to the talus bone. The default values of [0, 0, 0] means that the centre of the AFO bottom is located at the geometry centre of the talus bone in the MSK model.

***AFO\_cylinder\_radius:*** this variable defines the radius of the cylinder, which represents the size of the leg of the subject, on which the AFO will wrap. Therefore, this radii will also determine the radii of the circles for the top and bottom of the AFO stripes.

***AFO\_height:*** this variable defines the height of the AFO along the leg segment of the subject.

***AFO\_bottom\_location\_angle:*** this variable defines the locations of the endpoints of the AFO representation at the bottom. These endpoints are created along the circumferences of the circle at the bottom of the AFO cylinder, the locations of which are therefore defined using the central angles of these points, as shown below.



Figure 3: The definition of the bottom endpoints of the AFO stripes in the MSK model

Once the locations of the bottom endpoints of the AFO stripes are defined in terms of central engles, their local coordinates in the model global coordinate system can be determined using the following equations:



Where (XB, YB, ZB) is the local coordinate of one endpoint B at the bottom of the AFO, (X0, Y0, Z0) is the local coordinates of the centre of the circle at the AFO bottom (e.g. AFO\_bottom\_location). r is the radius of the cricle and θ is the centre angles of the endpoints (e.g. the AFO\_bottom\_location\_angle). The X axis is defined as the direction from the heel to the toe, while the Z direction is defined as direction from the medial and lateral. The positive θ is a clockwise rotation when looking from the knee to the foot.

***AFO\_stripe\_orientations:*** this variables defines the orientations of the AFO stripes, which is defined as the angle between the AFO stripe and the vertical direction when the AFO cylinder is unfold, as shown in below:



Figure 4: The definition of the stripe orientations in (a) 3D AFO cylinder and (b) the AFO cylinder when it is unfold

Once the orientations of the AFO stripes are defined, the locations of the endpoints of the stripes at the top of AFO can be calculated:

As shown in Figure 4a, length of curve TB’ = θ’/2π\*2πr = θ’\*r

In Figure 4b, length of TB’ = h \* tan ϕ

Therefore, the θ’ can be obtained as θ’ = h\*tan ϕ/r

The locations of the endpoints of the AFO stripes at the top of the AFO (T) can be then calculated as:



where (XT, YT, ZT) is the local coordinate of the endpoint T at the top of the AFO, (X0, Y0, Z0) is the local coordinates of the centre of the circle at the AFO bottom (e.g. AFO\_bottom\_location). r is the radius of the cricle, h is the height of the AFO, and θ is the centre angles of the endpoint B at the bottom (e.g. the AFO\_bottom\_location\_angle), and . ϕ is the orientation of the stripe.

The AFO stripe representation in the MSK model is modelled as ligament element, with the geometry defined as the 3D curve connecting the paired endpoints at the top and bottom of the AFO (e.g. the endpoints T and B) and wrapping the AFO cylinder. The slack length of the AFO stripe can be calculated as:

Lslack = h/cos ϕ

***Platform\_inclination:*** this variable defines the platform inclination angles for the drop landing simulation in three directions. By combing the angles in three directions, any inclination angles for the platform can be achieved.

1. ***The mechanical properties of the AFO materials***

The AFO stripes in the MSK model are modelled as nonlinear ligament elements, the nonlinear mechanical properties of which are characterised using a force-length relationship curve and a force magnitude, as shown in the Figure 4.



Figure 5: The force-length curve defined for the AFO stripe in the MSK model

***AFO\_Fmagnitude***: this design variable defines the force magnitude generated by the AFO stripe, the actual force generated by the AFO stripe during the simulation is determined by the AFO force magnitude multiplying the force length curve. For example, as shown in Figure 5, the force generated by the AFO stripe with an extension rate of 1.6 is about 1.16 N (e.g. 2N x 0.58).

***AFO\_FLrelationship\_one (\_two, \_three, \_four):*** These design variables define the nonlinear mechanical properties of the AFO stripes in terms of force-length relationship, as shown in Figure 5. This force-length relationship is composed of two vectors: the first vector (x values in Figure 5) is the extension rate of the AFO stripes during the simulation, which is defined as:

Extension rate x = L1 / L0

where L1 is the length of the AFO stripe after extension (stretch length), L0 is the original length before extension (slack length); the section vector (y values) is the force generated by the AFO stripe, however, the actual force generated by the strip should be the y values times the AFO\_Fmagnitude.

1. **Design variables for the mechanical properties of AFO strips**

The design variables of the locations for the bottom endpoints of the AFO strips, and the orientations of the AFO strips are straightforward.

For the mechanical properties of the AFO materials, we defined two design variables: one is the amplification of the force-length curve (i.e. fl\_am\_\* in the main code), the other one is the shift of the force-length curve (i.e. fl\_shift\_\* in the main code).

The amplification of the force-length curve represents the scaling of the force generated by the AFO strips, indicating the number of the fibres in each AFO strip, as shown in Figure 6a. For examples, if the baseline AFO material can produce a force of 0.6N at a strain of 0.4, then the new materials with a scaling of 60 (design variables of fl\_am\_\* times the FL\_amplification\_stepsize in the main code) can produce a force of 36N at the same strain of 0.4.

Similarly, the shift of the force-length curve represents the translation of the curve as shown in Figure 6b. For example, the shift value = -0.2 (is calculated by fl\_shift\_\* times FL\_shift\_stepsize -0.2 in the main code) means the curve is translated 0.2 units to the left. That means, for example, if the baseline AFO strip produce a force of 0.6N at a strain of 0.4, to produce the same force of 0.6N, the strain in the translated curve is 0.2 (0.4-0.2).



Figure 6: (a) the design variable of amplification for the mechanical properties of AFO materials, representing the scaling of the force (Blue: the baseline properties, Orange: the properties after scaling); (b) the design variable of shift for the mechanical properties of the AFO materials, representing the shift of the curve (Bule: the baseline properties, Orange: the curve after shifting to left).