Motion simulation in Hip simulator: A comparative study for oval wear track using MATLAB Software and Eulerian mathematical model.

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ABSTRACT: Multi-directional Motor Planning forms a crucial part in today's biomedical and robotics applications. In context to biomedical applications, the concept of multi-directional motor planning is utilized to realize Hip Joint Motion Simulation. It is only in the case of Multi-Directional Motion that the wear produced during Hip Joint Motion can be approximated to the real wear produced in the human body, and that the whole object of designing Hip Joint Simulators is to assess the wear rates produced in the motion which has significant impact on the human body and its functioning. In context of robotics applications, multi-directional motor planning is crucial in obtaining a functioning robotic arm / robotic hip joint, so that the robot designed has good functionality. Once the models have been studied, to obtain multi-directional motor planning, it is needed to plot Lissajous Patterns in 3 dimensions. These patterns are the slide tracks generated by the head of the hip joint on the cup and vice versa. In this project, various contemporary Hip Joint Motion Simulators will be studied. The ones which show closest real life motion and real life wear rate will be chosen, their mathematical models will be implemented in MATLAB and their motion thereby simulated and plotted. Once done so, the Lissajous Patterns associated with the slide tracks will be studied and the same be plotted in MATLAB. Research till date says that wear tracks-(similar to Lissajous patterns) can be represented by mathematical modeling such as the Euler Model. Using these formulae, researchers designed multi-directional motor in hip simulators (an instrument) and it is proven that same wear tracks can be reproduced. Most of the research papers state this fact but none show simulated results using MATLAB.

KEYWORDS: Biomechanics, Hip Joint Motion Simulation, Multi-Directional Motor Planning, Physics of Vibrations and Waves, Bioinstrumentation

1 INTRODUCTION

Joint simulators are important tools in wear studies of prosthetic joint materials. The type of motion in a joint simulator is crucial with respect to the wear produced. It is widely accepted that only multidirectional motion yields realistic wear for polyethylene acetabular cups. Multidirectionality, however, is a wide concept. The type of multidirectional motion varies considerably between simulators, which may explain the large differences in observed wear rates. At present, little is known about the relationship between the type of multidirectional motion and wear. One illustrative way to compare the motions of various hip simulators is to compute tracks made on the counterface by selected points of the surface of the femoral head and acetabular cup due to the cyclic relative motion. A new computation method, based on Euler angles, was developed, and used to compute slide tracks for the three-axis motion of the hip joint in walking.

The verified method was now applied to eight contemporary hip simulator designs. The use of correct motion waveforms and an Euler sequence of rotations in each case were again found to be essential. Considerable differences were found between the simulators. For instance, the shapes of the tracks drawn by the resultant

contact force included a circle, ellipse, irregular oval, leaf, twig, and straight line. Computation of tracks correctly for the most widely used hip simulator, known as biaxial, was made possible by the insight that the device is actually three axial. Slide track patterns have now been computed for virtually all contemporary hip simulators, and both for the heads and for the cups. This comparative analysis forms a valuable basis for studies on the relationship between the type of multidirectional motion and wear. These studies can produce useful information for the design of joint simulators, and improve the understanding of wear phenomena in prosthetic joints.

The slide tracks produced by the BRM Simulator indicate a very close agreement the biological wear rate associated with the human hip joint, whereas the slide tracks produced by the HUT–3 Simulator were in close agreement with the slide tracks produced in real life by the gait wave forms[2][3]. Hence, the two simulators were chosen for deeper study. Their slide tracks were verified mathematically by plotting their slide tracks in MATLAB and comparing those with the ones obtained experimentally.

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2 SLIDE TRACKS OF CONTEMPORARY HIP JOINT SIMULATORS

8 Contemporary Hip Joint Simulators were chosen as the basis of study viz BRM, HUT-3, AMTI, Munich, Leeds MK I and II, ISO/DIS, Durham Mk II, Pro SIM, BRM Non-Zero offset. A computation method, based on Euler angles was studied. The method was applied to the above 8 Simulators. The tracks produced by the Head on the Cup and vice versa were studied. Considerable differences were found between the slide tracks for different simulators.

The Euler sequence of rotations for any simulator design can be determined according to the following procedure, in which the rotations are made one at a time. The first rotation of the sequence is the one, which changes the orientation of the both remaining rotation axes of the simulator relative to the acetabular cup. This is because the reference coordinate system is fixed relative to the cup, as it is fixed relative to the pelvis in biomechanical studies of hip Joint. Similarly, the second rotation in the sequence is the one, which changes the orientation of the one remaining simulator axis relative to the cup. The third rotation in the sequence is the one which does not change the orientation of any simulator axis relative to the cup. [2]

In the case of a two-axis simulator, the first step in the procedure is skipped. The fact how the rotations are partitioned for the two components is unimportant because in tribology, it is the relative motion which counts. Determining the Euler sequence is an efficient way to enable an unequivocal analysis of any design and a direct comparison with any other design.

The force track shapes were circle (BRM), leaf (Munich), irregular oval (AMTI, Leeds Mk I), ellipse (ISO/DIS 14242-1, HUT-3), figure of eight (Durham Mk II), straight line (Leeds Mk II), and 'twig' (ProSim).By far the longest force track, 2.46r, was that of the BRM simulator, having also the lowest aspect ratio.[1]
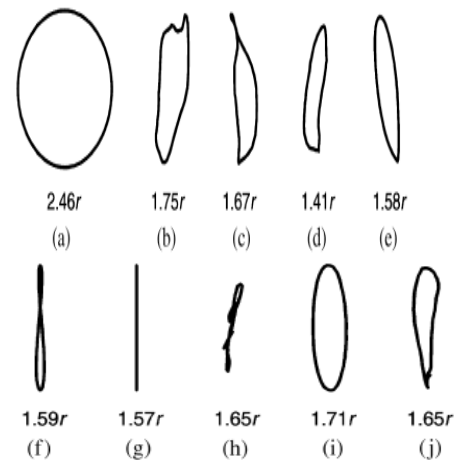

Fig: Force tracks together with their lengths: (a)BRM, (b) AMTI, (c)Munich, (d)Leeds Mk I, (e)ISO/DIS 14242-1, (f)Durham Mk II, (g)Leeds Mk II, (h)ProSim, (i)HUT-3 and, (j) gait (Johnson and Smidt, 1969).

Out of these, the slide tracks produced by the BRM Simulator indicated a very close agreement the biological wear rate associated with the human hip joint. Whereas the slide tracks produced by the HUT – 3 Simulator were in close agreement with the slide tracks produced in real life by the gait wave forms. Hence these two Simulators were selected for further study.
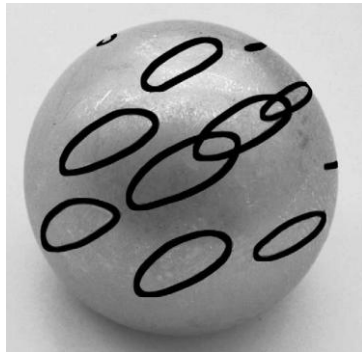
3 ANALYSIS OF BRM & HUT3 SLIDE TRACKS

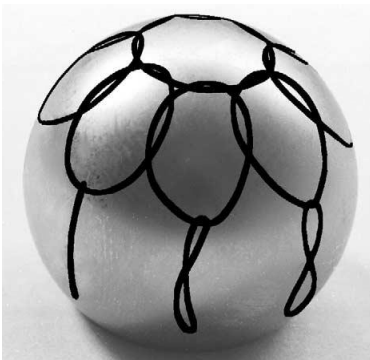The loads applied to the simulator as are shown:
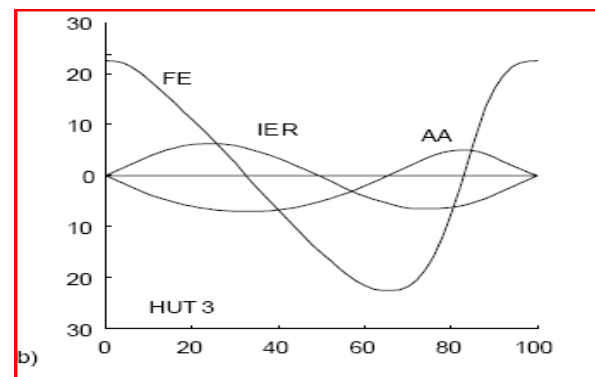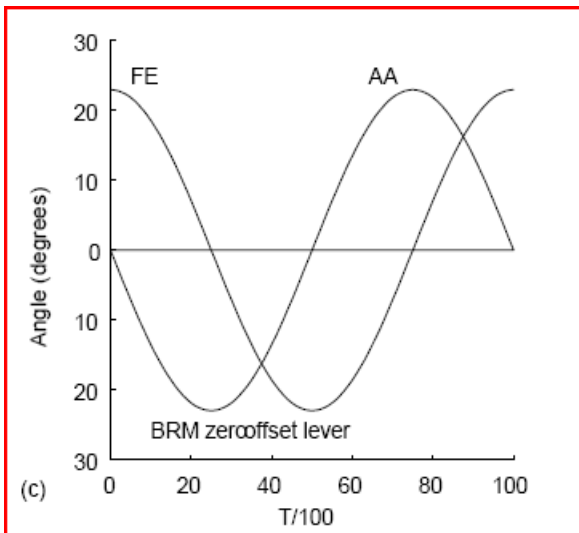
The tracks produced are as shown:
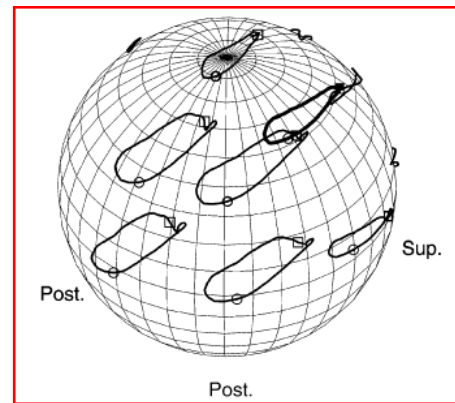

HUT-3

BRM

Fig: actual Gait waveform tracks

4 MATHEMATICAL MODELS OF BRM & HUT3 SIMULATORS

Computation of slide tracks using the mathematical model is done twice: first for the cup tracks and then for the head tracks.

4.1 Tracks on Cup by the Head [2]

- Fixed Co-ordinate system was fixed with respect to the cup, the axes being labeled as X, Y and Z and pointing in the medial, posterior and superior directions respectively.
- A moving Co-ordinate system was fixed with respect to the head, the axes being labeled as x, y and z respectively.
- The directions of the axes x, y and z with respect to the reference coordinate system were defined by the unit vectors u1, u2 and u3.
- The directions of the axes of the reference coordinate system were: $U1=[1,0,0]^T$, $U2=[0,1,0]^T$, $U3=[0,0,1]^T$.
- The FE, AA and IER rotations were made about the x, y and z axes according to the Euler sequence specified for the simulation.
- The rotation angles corresponding to the discretized FE, AA and IER waveforms were a_i, b_i, c_i. For i=1, 2, 3…..N, where N was the number of discrete points. In the present study, N was 100.
- A marker point P fixed to the head was repeatedly rotated from its initial position P_0 to a new position on the slide track. Each point P_i of the slide track corresponded to one set of rotation angles (a_i, b_i, c_i).
- The rotation for the sequence IER-AA-FE was $r_i = R_{xyz}(ai, bi, ci)r_0$ where r_0 was the initial position vector of the marker point, ri the position vector after the

rotation, and the rotation matrix Rxyz(a, b, c) is given by

$$\begin{bmatrix} c_1c_2 & c_1s_2s_3 - c_3s_1 & s_1s_3 + c_1c_3s_2 \\ c_2s_1 & c_1c_3 + s_1s_2s_3 & c_3s_1s_2 - c_1s_3 \\ -s_2 & c_2s_3 & c_2c_3 \end{bmatrix}$$

Where c1, c2, c3 is cos(a), cos(b), cos(c) respectively
And s1, s2, s3 is sin(a), sin(b), sin(c) respectively

- The track was drawn by connecting all points defined by ri = 1, 2, 3…..N; N=100

4.2 Procedure

- For the computation, we need 100 sets of the values (ai, bi, ci) which are obtained from the waveforms as below.
- $U^1=[1,0,0]^T$, $U^2=[0,1,0]^T$, $U^3=[0,0,1]^T$ are fixed for the XYZ Co-ordinate system for the cup.
- u^1, u^2 and u^3 are fixed for the xyz Co-ordinate System for the head based on the relative position of the head with respect to the cup.
- r_0, the initial position vector of the marker point, is fixed based on the relative position of the initial marker point position with respect to the origin of the xyz co-ordinate system, viz. the head.
- From (1), 100 points are obtained, by plugging in each of the 100 sets of (a_i, b_i, c_i) values. These points all joined will then give the slide track motion with respect to the cup.
- For the head tracks, 100 sets of (u^1, u^2, u^3) were obtained from 100 sets of the values (ai, bi, ci) by using (3)
- A set of 100 matrices Li where obtained from the 100 values of the set (u^1, u^2, u^3) by using (2)
- From this, 100 values of ri are generated, and all these are joined to give the slide track of the motion with respect   to head. The (a, b, c) values are given in the previous graphs.
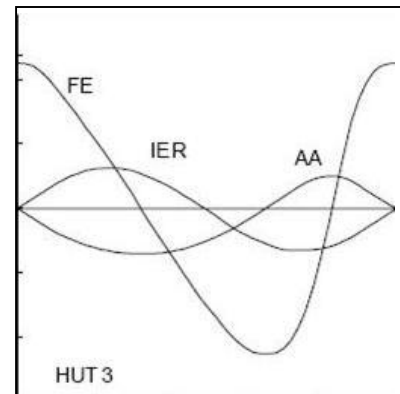
5 OBTAINING INPUTS FOR THE SIMULATION

- We need 100 sets or more values of the arrays (a, b, c) obtained from the graphs of FE, AA and IER inputs provided to HUT-3 Simulator as shown before.
- The problem is that the values are available in the form of a graph, which was available only in the form of a
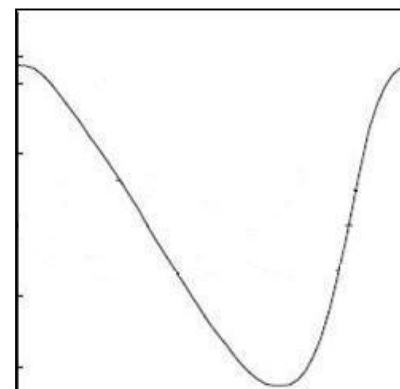
JPG Image.
- Hence, MATLAB Image Processing Toolbox was used to obtain discretized values of the FE, AA and IER inputs for the simulation

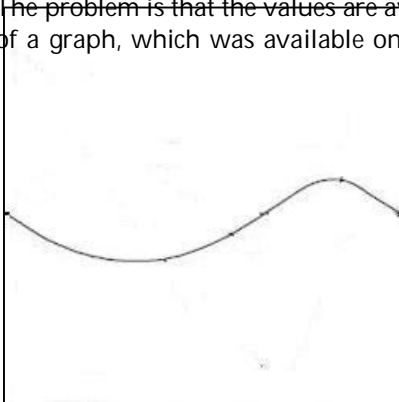### 5.1 Separation of the FE, AA and IER Images

The graph jointly available for FE, AA and IER was separated into FE, AA and IER respectively using paint.

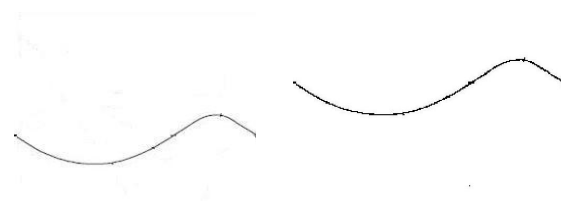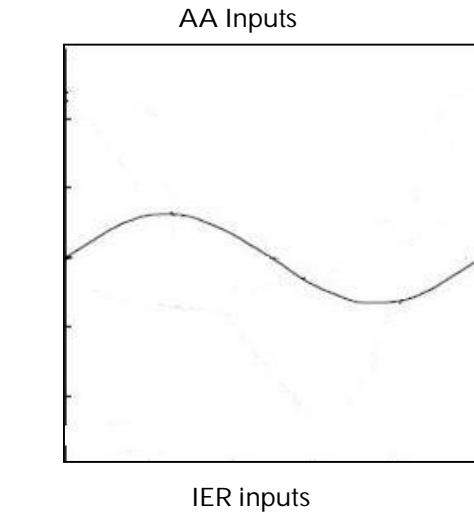FE, AA and IER joint inputs

FE Inputs
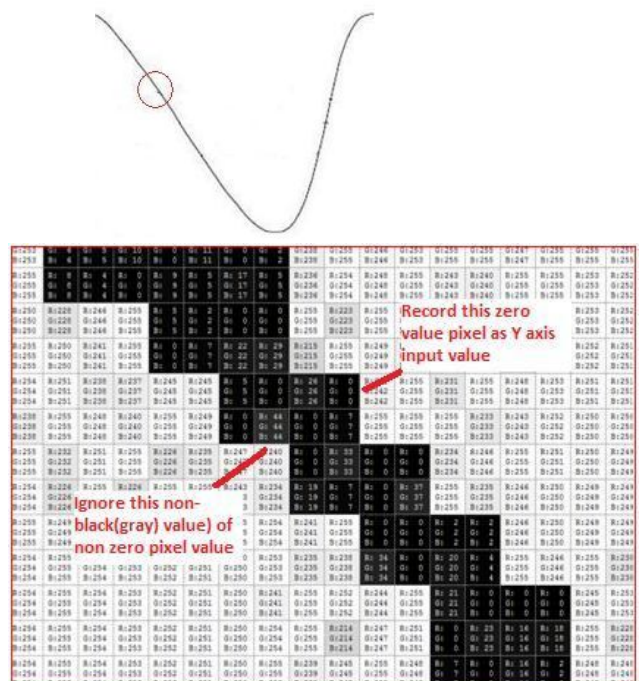
AA Inputs

IER inputs

5.2 Thresholding the FE, AA and IER Images

Thresholding is the simplest method of image segmentation. From a grayscale image, thresholding can be used to create binary images. In our graphs, we had two colors, black and white. However, the black did not have a uniform pixel value Hence, the image was thresholded into pixel values of two one for black, and one for white, so that the graph looked a uniform black color, and the rest, was uniformly white. Basically, a certain threshold was decided, If any point was above it, it was made black, else it was made white. So, overall, we got a uniform black and white image
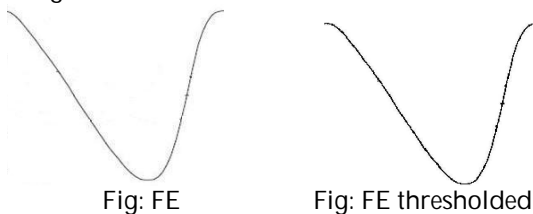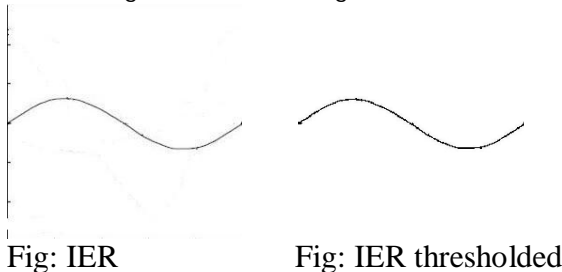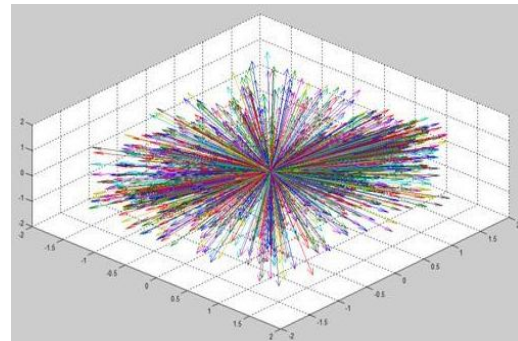

Fig: FE   Fig: FE thresholded

Fig: IER   Fig: IER thresholded

Fig:AA   Fig: AA Thresholded

5.3 Obtaining Unscaled Input Values from Thresholded Images

The pixel value for any black point on the graph is 0. So, we ran a 'for' loop, along the X axis of the graph In the 'for' loop for every row, we ran a second 'for' loop. It ran along the Y axis in the second loop, if we came across a pixel value of 0, then it meant it is a black point that corresponds to a point on the graph. Hence the pixel value was noted. This was done for every pixel value along the X axis. Hence, for every pixel along the X axis, we obtained one value. For the Y axis corresponding to the graph point this was indeed the input value for the corresponding FE, AA and IER value

Lets inspect the circle part of the following image
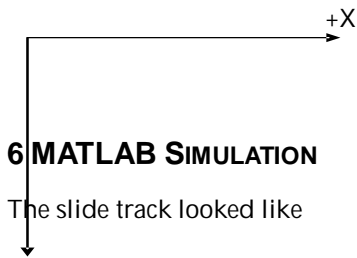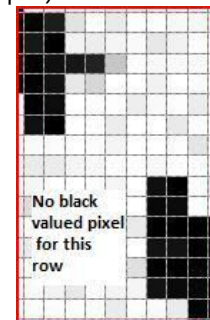
- Now, this had to be scaled, into the correct range.
- Basically, the XY coordinates in MATLAB were as follows:

+X

6 MATLAB SIMULATION

The slide track looked like

+Y

- The Y values were all multiplied by -1 to make them correspond to the regular +Y direction.
  the actual input provided. Hence, 325 were added to all the Y values.
- The peal value of 198 in Y for the graph corresponded to a value of 23 in the actual input provided. Hence, the values were all multiplied by 23/198
- Overall the function was, $p=(23/198)*(325-input)$
- The inputs were then used to plot the tracks as per the model explained before.

The dissimilar long arrows at some points are due to the irregularities in the image that we had. There were some points on the graph, that we had no pixel of zero value in Y axis loop that we ran. So, in that case, the Y value immediately assumed the initial value of 0 assigned to it in the for loop start. This value of 0 got scaled into the maximum value of 23 while using the scaling equation
$p= (23/198)*(325-input)$

Hence, due to these maximum values (abrupt ones), we got abruptly long position vectors in some cases. This defect can only be removed if we can get a better quality image or the actual input values from the authors of the research paper that was referred while obtaining these inputs.

7 CONCLUSION

Research to date shows experimental proof on Slide tracks produced by Hip Joint Simulators mathematically modelled using the Euler Angle Method. Another way to reinforce the Euler Angle Method for the development of the Mathematical Models of Hip Joint Simulators would be to implement these Models in MATLAB.[1]

We implemented the Mathematical Model of HUT-3 Simulator based on Euler Angles in MATLAB. The slide tracks simulated resembled an oval. This was found identical to the slide tracks produced experimentally by the HUT-3 Simulator. Hence, it can be verified that the Euler Angle based Mathematical Model for HUT-3 Simulator is the right model for the simulator.

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