Adult/Child Musculoskeletal Model and Motion Analysis Comparison

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Abstract

Given the scaled model of a child reconstructed through the different walking experiments within an OpenSim environment, we performed interfacing OpenSim-Matlab and implemented an equivalent kinematic model in Matlab. The aim is to provide a visual representation, which is useful for the detection of gait peculiarities. Additionally, adult kinematic model has been implemented based on the kinematic and MOCAP marker data. A comparative motion analysis between the child and the adult has been performed.

I. Project Description

The underlined idea of our project is to provide a Matlab visualization tool for human musculoskeletal models of an adult and a child together with a Matlab visualization tool for motion analysis and motion comparison – the study is mainly concerned with understanding of the human walking patterns throughout the gait cycles and, in particular, in understanding how gait properties are changing with age (Figure 1).

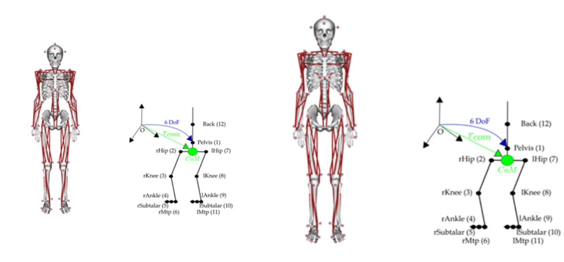


Figure 1: *Child/adult models.*

Although the implemented visualizing utilities can be extended for a dynamic comparison, we mainly focused on the kinematic analysis. From the biomedical point of view, the kinematic analysis plays an important role to identify and better understand gait deviations. This is also important to evaluate the effects of the treatments on gait deviations when they are needed (e.g. this is a necessary step towards the design and evaluation of rehabilitation exoskeletons). In order to have a clinically relevant study, spatiotemporal parameters and joint angles patterns have to be tracked over a gait cycle. Therefore, we are interested in the development of such a tool that will be able to allow effective tracking. In the field of computer science, effectiveness means that all performed computations need to be precise/accurate and all visualizations need to be representative. However, at the same time, one of the main requirements and desired properties of our software was adaptability, since we are interested in flexible and adaptive tracking tools. This provides a possibility to follow an evolution of the rehabilitation process with an age of the patient. Consequently, from the conceptual point of view, our developed utilities approach the challenge of adaptability. Our contribution consists of two functional elements:

1. Tracking the evolution of the marker trajectories (i.e. positions);
2. Tracking the evolution of inverse kinematics (i.e. joint angles).

II. Data

The already preprocessed experimental data has been initially collected by a motion capture (MOCAP) system: during experiments, 2D markers positions were registered for each camera and for each frame together with force platform analog signals. The 3D marker positions then were reconstructed using triangulation. Data is acquired at 200Hz over an interval of 2.5s with a resulting resolution of 0.005s and 500 timesteps. Considering the human body as a bio-mechanical system, we can describe this system by choosing one or more descriptive features during motion, such as the positions of markers or joint frames as well as joint angles or the relative orientation of body parts. The information, acquired by looking at these particular features, is collected and spread over different files. Each of these files is organized in a tabular way by rows and columns. Each row contains the whole configuration at the given timestep and therefore completely describes the current state, while each column contains the whole time series for a single feature.

Detailed information about the data files, used in our modeling pipeline, can be found in the following subsections (about child and adult separately).

i. Child

Name: Sirine;
Age: 7 y.o;
Height/Weight: 1.20m/20kg.

Sirine is a healthy child who participated in the original gait experimental study regarding her twin-sister with spastic cerebral palsy. Nine walking trials were recorded for her during experiments, yielding the following information:

`marcheN.trc` – recorded experimental time series of markers positions (N corresponds to the number of the walking trial) expressed in a Ground reference frame, where the motion takes place along the x-axis, and the up-right position follows the y-axis. Positions (x, y, z coordinates in the Camera frame) for the 56 experimental markers have been provided by the MOCAP system for Sirine, but only half of them (simplified model: torso and lower body) have been involved in the further modeling steps. Their labeling information and exact positioning in terms of the body segments is represented in the Table 1. An example of the marker placement for the torso and pelvis can be found in the Figure 2.

`sirine.osim` – the model, obtained as the result of an OpenSim scaling procedure. The OpenSim Scale Tool moves the virtual markers

Segm	Markers
Torso	C7 T10 SUP STRN
Pelvis	LASIS/RASIS LPSIS/RPSIS
L leg	LGT LATT LMFE LLFE RAJC
R leg	RGT RATT RMFE RLFE CD
L foot	LSPH LLM LCAL LMFH5/1 LTT2
R foot	RSPH RLM RCAL RMFH5/1 RTT2

Table 1: *Sirine: 30 body markers structured by the body segments. Segm – body segment, L – left, R – right.*

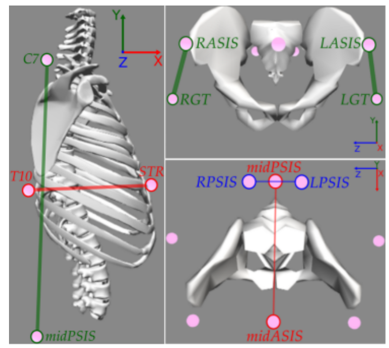


Figure 2: *Sirine: torso and pelvis markers.*

on the model so that their positions match the experimental marker locations. A representation of the scaled model in OpenSim is drawn in the Figure 3.

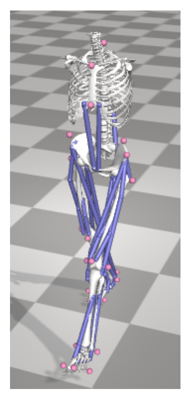
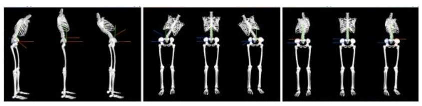


Figure 3: *Sirine: OpenSim model.*

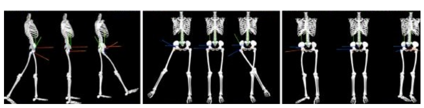
`marcheNik.mot` – contains the solution of the inverse kinematics problem at each timestep. The resulting information about the evolution of the joint angles during motion is then arranged by rows and columns, following the criterion, already described in the introduction. Note that the joint angles are labelled in the biomedical terminology (given in the lists and pictures below).

1. Pelvis (w.r.t. World):
   (a) Anterior/Posterior Tilt;
   (b) Left/Right Roll;
   (c) Left/Right Rotation;

2. Trunk (w.r.t. Pelvis):
   (a) Flexion/Extension;
   (b) Left/Right Bending;
   (c) Left/Right Rotation;



3. Hip (w.r.t. Trunk):
   (a) Flexion/Extension;
   (b) Abduction/Adduction;
   (c) External/Internal Rotation;



4. Knee/Ankle:
   (a) Flexion/Extension;
   (b) Plantaflexion/Dorsiflexion;
   (c) Eversion/Inversion;

ii. Adult

Height/Weight: 1.71m/71kg.

`raw data.txt` – analogically to the `marcheN.trc` for Sirine, contains time evolution of the markers positions in the Camera frame (expressed in the millimeters instead of meters), but with the different set of markers (Plug-In Gait Markers: details in the Table 2). In particular, the number of used markers is reduced in the comparison with a child: 21.

The mapping between the information, contained in the `marcheN.trc`, and the `raw data.txt` is given by a rotation of 90 degrees around the y-axis. This ensures that a point (x, y, z) in the adult Ground reference frame has a new set of coordinates $((z, y, -x))$ in the rotated Sirine Ground reference frame.

Segm	Markers
Torso	C7 T10 CLAV RBAK STRN
Pelvis	LASI/RASI LPSI/RPSI
L leg	LTHI LKNE LTIB LANK
R leg	RTHI RKNE RTIB RANK
L foot	LHEE LTOE
R foot	RHEE RTOE

Table 2: *Adult: 21 body markers, structured by the body segments. Segm – body segment, L – left, R – right.*

`kinematic data.txt` – contains the kinematic data of the adult, reconstructed from MOCAP system measurements, consisting of positions of the origins of each joint frame (trunk, pelvis, left/right femur, left/right tibia, left/right foot) w.r.t. the Camera frame and rotation matrices of each of these frames w.r.t. the parental one (rotation matrix which expresses the base of trunk in the pelvis frame, rotation matrices which express the bases of left/right femur in the pelvis frame, rotation matrices which express the bases of left/right tibia in the left/right femur frames, and so on). The matrices have been obtained as a sequence of roll-pitch-yaw rotations and then flattened out so that all nine elements can be found in a row. Hierarchical information about the frames is represented in the Figure 4.

III. Framework

As said above, the scaled model of Sirine has been used to generate a simulation of the child's gait within an OpenSim environment. Then, source OpenSim files with experimental markers trajectories and experimental generalized coordinate values have been used as an integration OpenSim-Matlab to derive q representation of the Sirine's model in Matlab. There it can be ultimately compared with an adult kinematic model, based on the source text files. All further developments of our framework

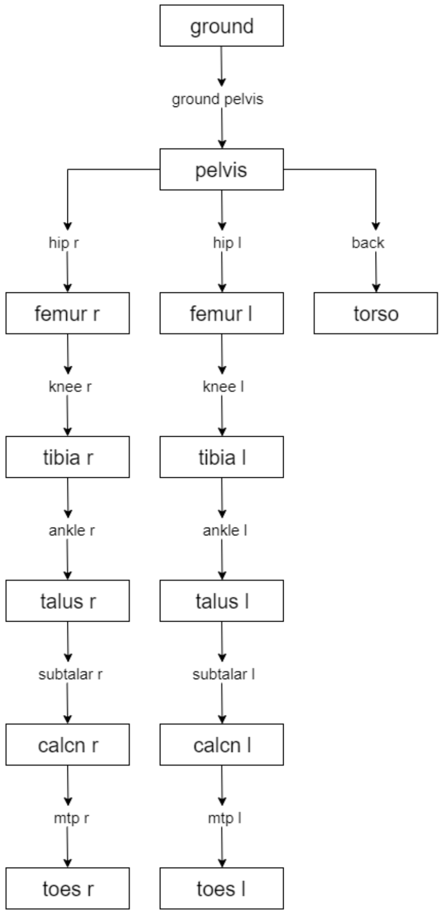


Figure 4: *Adult: hierarchy of frames.*

are Matlab scripts, which are represented and explained in the current chapter.

i. Sirine model

Script: `Sirine model.m`;
Performs: Preprocessing (reformatting of tabulations) and arranging the marker time series in an ad-hoc structure;
Outputs plotted: Musculoskeletal unitary elements (torso, pelvis, knees, feet, calves, quads and hamstrings) as a set of coordinates connected by the line segments; Markers per body segment;
Observations and Implementation details: Due to the file structure, we used the `fgetl` Matlab function in order to read each file row by row. Each row has been split into an element-wise manner, obtaining the full state/configuration at the i-th time step. Since we are interested in the time series of each marker to be able to plot the geometrical Matlab model, the elements of each row have been arranged in a column, containing the full evolution of a specific marker. Iterating over all timesteps, we obtain a visualization of the motion. When considering just specific timesteps, we obtain a static pose of the represented body during motion;
Reference: Figure 5, Figure 6.

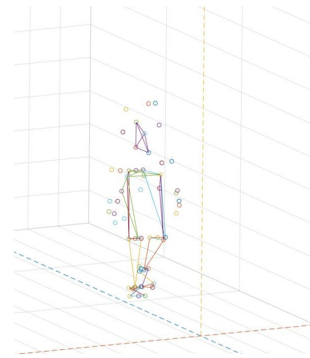


Figure 5: *Sirine: Matlab model with markers.*

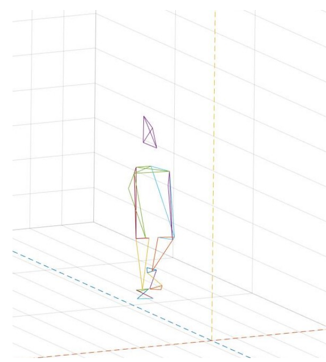


Figure 6: *Sirine: Matlab model without markers.*

ii. Adult model

Script: `Adult model.m`;
Performs: Preprocessing of both text files (kinematic data and marker data) and arranging marker time series, origins of the joint reference frames and rotation matrices in an ad-hoc structure;
Outputs plotted: Stickman model; Rotating joint frames; Body segments (trunk, pelvis, femurs, tibiae, feet); Markers per body segment;
Observations and Implementation details: In order to plot also the relative orientation of each frame w.r.t the parental one, the elements of the rotation matrices (contained, as previously said, into the `kinematic data.txt` file)

have been used. The pelvis has been considered fixed and it's axes have been plotted as simple orthogonal unitary lines and then multiplied by the appropriate rotation matrices, using a control-flag criterion to obtain back the rotated frame;
Reference: Figure 7, Figure 8.

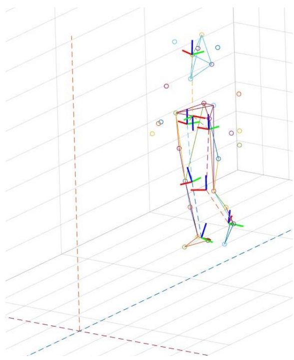


Figure 7: *Adult: Matlab model with markers.*

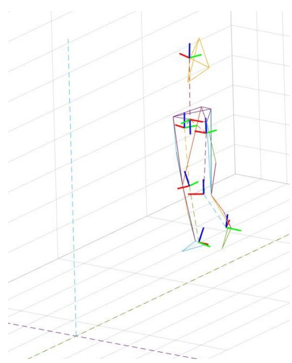


Figure 8: *Adult: Matlab model without markers.*

iii. Cartesian comparison

Script: `Cartesian comparison.m`;
Outputs: Parallel animated simulation of both adult's and Sirine's gaits.
Observations and Implementation details: Since the child's and adult's data has been collected within different reference frames, the child's Ground reference frame has been chosen as the World reference frame, and therefore a sequence of geometrical transformations over the adult's model has been performed in order to express the motion coherently with the child's one. This helps to avoid overlapping and indirection effects. Different perspective views are achievable by changing the camera position and orientation;
Reference: Figure 9, Figure 10.

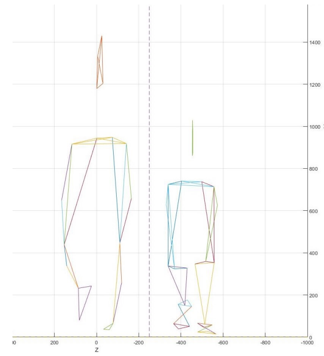


Figure 9: *Adult and Sirine: Front view.*

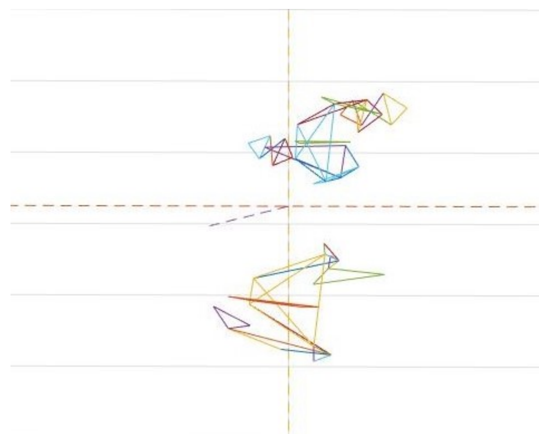


Figure 10: *Adult and Sirine: Top view.*

iv. Marker comparison

Script: `Markers comparison.m`;
Outputs plotted: Motion paths of the selected markers (3D);
Observations and Implementation details: A system of control variables has been used to selectively plot few specific trajectories in order to derive a more informative comparison. The same geometrical transformations as for the Cartesian comparison have been used;
Used: Performing comparison of markers trajectories.

v. Angle comparison

Script: `Angle comparison.m`;
Outputs plotted: Joint angles trajectories (2D);
Observations and Implementation details: These plots describe the evolution in time of

the particular angles of interest. The child's angles are contained inside the marcheNik.mot files, meanwhile the angles for the adult have been computed using the analytical inverse kinematic formulae, considering the general form of a 3D rotational operator, which is obtained as a sequence of three rotations around the z, y and x axes (roll, yaw and pitch or Euler angles). Since Sirine's and the adult's joint frames seem to have different initial absolute orientations, the compared angles turn out to be out of the phase and inverted. In order to do an informative comparison, it has been necessary to transform some of these angles by shifting along the time axis or correcting the initial phase and inverting them, i.e. handling the phase shifts or sign differences;
Used: Performing evaluation of a joint angles evolution.

IV. Motion Analysis

Finally, based on the aforementioned framework, we can perform motion analysis and a subsequent comparison of both models.

i. Markers trajectories

By plotting the whole marker trajectories for Sirine and the adult within the same environment, it is possible to derive information about the general gait properties, changes which these properties experience by age and subject-specific properties.

Analysing the Sagittal plane trajectories for both the **torso** (Figure 11) and **pelvis** (Figure 12) sets of markers, it becomes clear that Sirine's motion is more irregular than the adult's one. Considering the **knee** region (Figure 13), for Sirine we can observe unexpected peaks and a widened range of amplitude around the y-axis, while on the contrary, the adult's markers trajectories remain periodic and smooth. Additionally, Sirine's unnatural motion (dragging of the foot) is observable by looking at the low peak in the LTT2 marker trajectory (Figure 14, purple curve, the second gait cycle).

Looking at the Transverse plane, the most interesting marker trajectories are again the **knee** and **foot** ones. Sirine's knee plot (Figure 15) shows some a-periodic peaks with high slopes towards half of the motion, meanwhile the adult's knee trajectories are smooth and

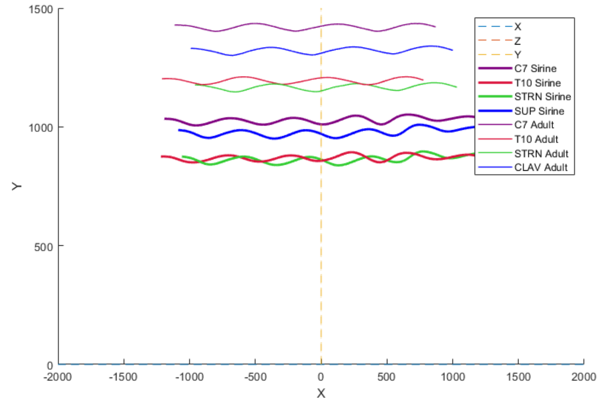


Figure 11: *Marker trajectories: Torso, Sagittal plane.*

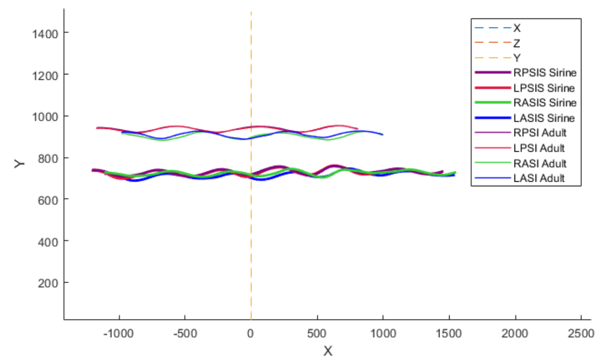


Figure 12: *Marker trajectories: Pelvis, Sagittal plane.*

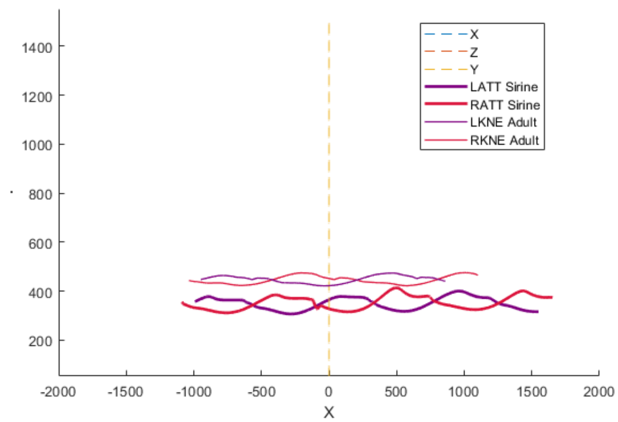


Figure 13: *Marker trajectories: Knee, Sagittal plane.*

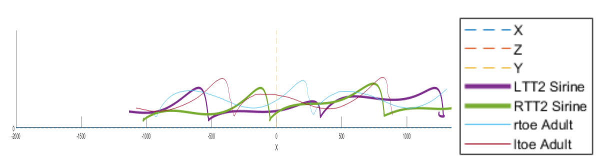


Figure 14: *Marker trajectories: Toe, Sagittal plane.*

periodic. Considering the feet plots (Figure 16), peaks for the right and left foot markers have the opposite directions (feet inversion during swing) in the adult case, while in Sirine's case they are co-directed (right toe eversion).

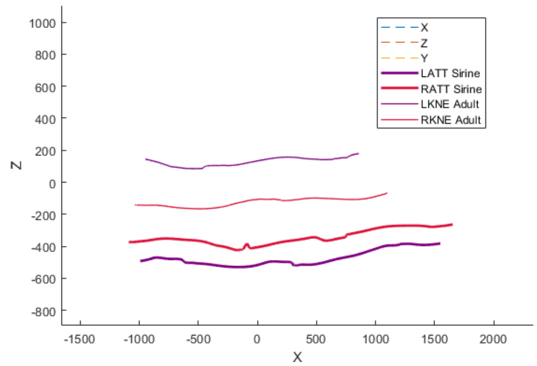


Figure 15: *Marker trajectories: Knee, Transverse plane.*

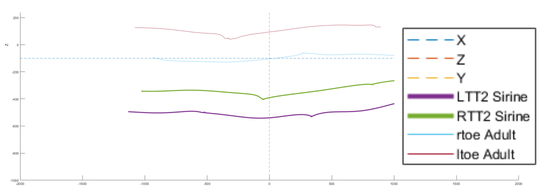


Figure 16: *Marker trajectories: Toe, Transverse plane.*

The Coronal plane analysis provides us with information about Sirine's non-straight walking, which can be concluded through the observation of the oscillations along the z-axis (wider for her than for the adult, despite of the lower dimensionality of the body segments) and through the marker trajectories overlapping (holds for all body parts, e.g. for the **ankle** in the Figure 17).

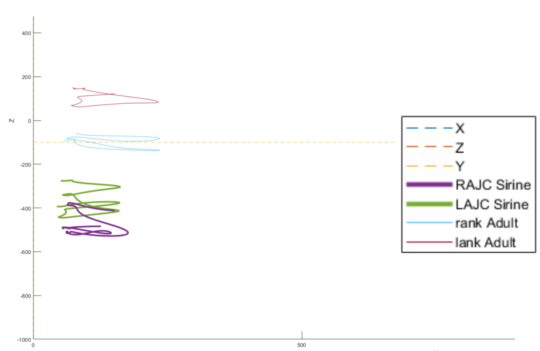


Figure 17: *Marker trajectories: Ankle, Coronal plane.*

ii. Inverse kinematics

After completing the markers comparison, the analysis has been moved towards the inspection of angle evolution. This kind of analysis is more complicated mainly due to the discrepancies, pointed out in the Framework section. Nevertheless, after application of the appropriate transformations and performing of the disambiguation of notations, coherent information has been successfully retrieved and the most informative for the comparison angles have been determined: Hip Extension/Flexion, Knee Extension/Flexion and Ankle Plantaflexion/Dorsiflexion.

Firstly, let us consider **Hip Extension/Flexion** (Figure 18). Notice that the certain bias between curves is still present, even though the difference between the reference frames for the adult and for Sirine has been corrected by appropriate transformations. Apart from that, the adult's curves are smooth and characterize the movement of a constant rotation, but for Sirine the hip extension phase has a characteristical angular acceleration pattern. Additionally, higher slope in the Sirine's curves is conditioned by the higher angular velocity along the hip.

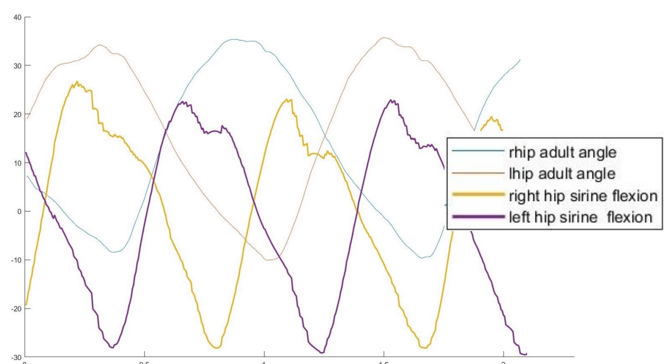


Figure 18: *Inverse Kinematics: Hip Extension/Flexion.*

Secondly, **Extension/Flexion** of the **knees** has its own peculiarities. Swing and step phases for both Adult and Sirine are clearly visible in the Figure 19. The non-straight walking assumption, made about Sirine during the marker trajectory analysis, is again confirmed by the fact, that the joint angles of the consecutive gait cycles are different. Then, the asymmetry between left/right knee is present, since the amplitude for the right knee is higher, than for the left one. Meanwhile, this does not remain true for the adult's curves, where amplitudes are equal up to a negligible constant. Their overall range is reduced in the comparison with Sirine.

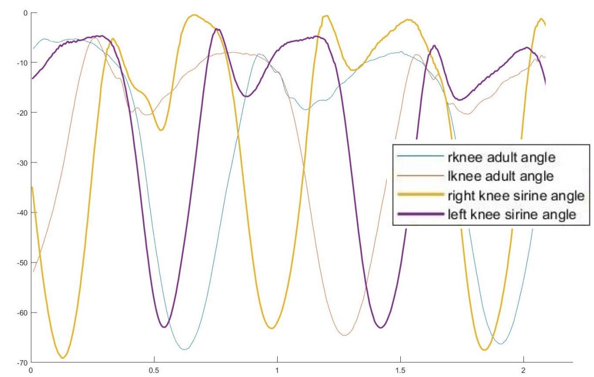


Figure 19: *Inverse Kinematics: Knee Extension/Flexion.*

Thirdly, comparison of the **Ankle Plantaflexion/Dorsiflexion** (Figure 20) was a bit complicated to derive due to the different naming conventions used in the source files. Therefore, it is an approximation to some extent. In general, ankle patterns look quite stable. However, the amplitude of oscillations in Sirine's curves for both left and right ankles is significantly higher than in the adult case, and jumps, corresponding to the change of direction, are more rapid.

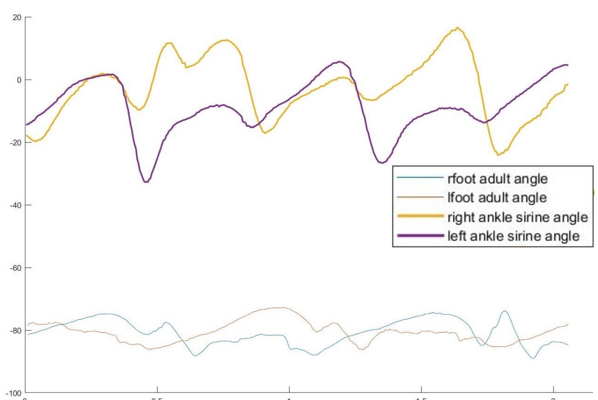


Figure 20: *Inverse kinematics: Ankle Plantaflexion/Dorsiflexion.*

iii. Conspicuities

Of course, our comparative analysis is influenced by the scaling properties of the body segments (e.g. smaller heights/wights of body parts of Sirine lead to a larger number of gait cycles and smaller step sizes), but still, some scale-independent conclusions about the child's gait peculiarities in comparison with the adult's ones can be made.

Sirine's slightly corrupted (non-straight) walking is clearly observable from the motion patterns and is characterized by the following list of observations, made in the body-segment-by-body-segment mode:

1. Upper body (torso and pelvis) shows small irregularities in oscillations;
2. Knee buckling seems to be a specific characteristic of the child's gait;
3. Ankle motion is quite regular and periodic;
4. Right toe is dragged while performing Flexion/Extension rotation;
5. Angular motion is accelerated and wider ranged.

V. Conclusion

The Matlab visualization software for the human musculoskeletal modeling and a Matlab visualization tool for the individual and comparative motion analysis have been implemented. The overall goal of understanding human gait patterns and their evolution throughout the temporal domain using the aforementioned implemented software has been achieved.

We can conclude, that the walking patterns for a child's gait characterize more perturbed, frenetic and unstable motion. It is hard to say, if all of the brought out by analysis «unnatural» patterns in the Sirine's motion should be treated as a matter of her age or as a predisposition to the similar imperfections as in the case of her sister (in a significantly reduced way though). However, even without an equilibrium analysis, some observations about development with age of the equilibrium/coordination-related movement abilities can be made. In particular, our performed motion analysis leads to the consideration, that aforementioned abilities are not fully developed during the earlier stages of life (when the human body is yet undeveloped).

References

[1] *M. Marchitto*

Motion Analysis for Children with Cerebral Palsy: a Comparative Study on Twins.

[2] *https://simtk-confluence.stanford.edu*

OpenSim software official documentation.