Foot Gait Analysis and Simulation

Ľudovít Lučenič
Peter Argaláš
Zuzana Halanová
Martin Šoltis

Faculty of Informatics and Information Technologies
Slovak University of Technolgy
Bratislava / Slovakia

Abstract

This paper presents the current state of a research project oriented in computational support of medical diagnosis. The project concerns further with the support of orthopaedics. It consists of conversion of a patient's gait into a motion of an animated lower body part model. The angular velocities analysis of the lower extremities joints is meant to be carried out after the gait is captured. The problems of synchronization of multiple cameras have been managed so far as well as experiments on skin colour model of image segmentation have been made. Another contribution of the project up to this day is a complete analysis of the human skeleton motion in an ankle and a heel region from medical point of view. We have realized this analysis in more details than other projects do at present.

Keywords: medicine, skeleton model, gait analysis, ankle, motion grabbing, synchronization, segmentation, skin colour model, computer vision

1 Introduction

Nowadays, human skeleton modelling is a widely used technique in many areas of research and in practice. Apart from rather wide-ranging application in the field of film animation one area is also that of medicine. The computational support of medical diagnosis is based on several practical requirements. Maybe the most important is the fact that diagnosis is highly subjective activity (except for solely numerical results of assays). As such it is rather noticeably burdened with a subjective error. To eliminate this error we can create a model, whose behaviour corresponds to one of a patient. So it is possible to quantify some of the aspects and concretize potential error. Another requirement related to practice is for example the possible comparison of multiple motions of more patients at the same time or possibly the comparison with an ideal gait.

The main aim of our work is to provide two-level computational support for an orthopaedic workplace oriented mainly on corrections of gait disorders originating or effecting in the heel motion. The first level is to determine the angles of joint swings (particularly the ankle region) during the normal gait of a patient on a treadmill. We intend to present these swings simultaneously in time for chosen set of joints. The second motivation of our research is to bring the skeleton model into a motion in accordance with the real gait motion of a patient.

The motion of bones in an ankle during the gait is rather complex. It comes to the simultaneous rotational motion of bones around one or more axis in multiple phases of translational movement of a leg. This motion in its complexity seems to be a rotation along the spherical surface which is relatively difficult to model.

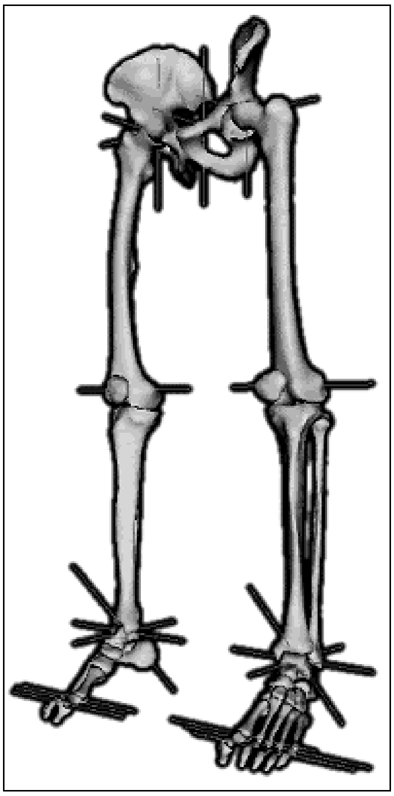


Figure 1: Lower extremities model with displayed axis

We can specify the I/O characteristics of the project as follows: captured gait of a patient is transformed into the motion of (unified) skeleton model; using the analysis of the data that we use for model animation, we reconstruct the time function of joint swings, which we subsequently present to the user.

The rest of the paper is organized in the following manner: section 2 describes similar systems we found on the issue; section 3 contains in-depth problem decomposition into subtasks; in sections 4 and 5 we aim at synchronization and segmentation problems and finally section 6 describes the model of the lower part of the human skeleton we work with (see Fig. 1).

2 Related works

We managed to find several projects dealing with similar issue as we do. All of them consider the motion of lower extremities, but none of them put such emphasis on the ankle region as we need to do to meet our objectives. There are also the following programs dealing with the issue apart from our research: Codamotion Analysis [2], APAS/Gait [3], Visual 3D [4].

The aforementioned systems do not operate in real time. Gait analysis (the first step) is done before the whole motion is animated. These applications allow tracking the movements of extremities in the model as well as in a graph, but they do not let the user to manipulate the model. The user can pick out what is to be drawn in the graphs. The graphs are only two dimensional and the position of tracked points is determined by only two coordinates as well. The swings of extremities aside are not tracked. Tracked are only those ones in the direction of a gait where the tracked point level is being monitored. There can be depicted not only the positions of tracked points, but the velocities, accelerations, forces, moments, powers and angles between them as well as in the graphs. These programs incorporate variable playback speed of animation and view angle change features.

Codamotion Analysis System allows the user to set up the tracked points to be connected. Hence, the completely different part of a body can be tracked through correctly connected points. The wire-frame model is thus drawn no matter what part of a body it is. Using cursors simplifies the work with graphs. APAS/Gait program allows working with two gaits simultaneously and thus enables their mutual comparison.

Our work builds upon results of last year's student team project titled Animation and visual analysis of human gait [1]. We took over their lower part skeleton model and fixed it to represent the real ankle motion from the medical point of view. Generally we continue to work on the project with emphasis on the automation of the whole process.

3 Problem decomposition

The issue of lower extremities motion animation during gait consists of more aspects, which must be taken into account. Firstly, it is the process of gaining data for the animation. Its input is a camera captured gait of a particular patient and the output is the data representing his/her motion. However, these data are independent of the particular leg of a patient – of its shape, size or natural position. Next aspect to be considered is the sense of the data. The aim of the project is to visualize and analyze the human gait so the most important object of our interest seems to be the ankle conceivably the tip of the sole where midpoints of all joint rotations in the feet region are situated. Not to a less extent the data analysis from medical point of view should be considered.

Capturing the gait of a patient comprises just the first step of gait animation in practice. The rest of whole process can be divided into the following subtasks:

- sole marking
- video recording
- digitalization and image sequence extraction
- synchronization of video-sequences taken simultaneously from different angles (e.g. based on the common event captured on the video)
- pre-processing of two dimensional images for purpose of segmentation simplification
- segmentation – markers or joint recognition
- markers to joints correspondence
- markers or joints (three dimensional) coordinates determination
- transformation of coordinates to the format of model subsystem
- conversion of sequential coordinates changes into the format of animation subsystem

In this paper we primarily focus on the synchronization and segmentation issues and the correct representation of a model of a lower part of the human skeleton.

4 Synchronization

As we chose shooting the scene with two cameras (two projections), we needed to work out the synchronization of these two recordings. We have investigated so far the synchronization with the flash. Our particular method was to determine the flash presence in each single frame with the values of RGB model components. The value of RGB components is higher in the frames spotting the flash (Fig. 3). In separate frames we can define the value of RGB model elements and then determine the average value. We are able to find synchronizing impulse by comparing the average values of RGB components in three straight consecutive frames. There is a minimal difference in the average values in those subsequent frames which are either both flash-marked or not. We found out the fact that the flash spots only one single frame (using 25 fps camera).

There are sequences (a-e) of three to four images depicting captured impulses of the flash in Figure 3 along with particular histograms at the bottom on the right. The mutual positions of a flash and a camera for single sequences are then displayed in Figure 2. Results of the analysis we made are as follows: perpendicular flash position (Fig. 2e), flash/camera angle of 45° (Fig. 2b) and parallel beams of a flash and camera (Fig. 2a,c) are appropriate as internal synchronization information. The flash positioned behind an obstacle (Fig. 2d) is absolutely unusable for this purpose.

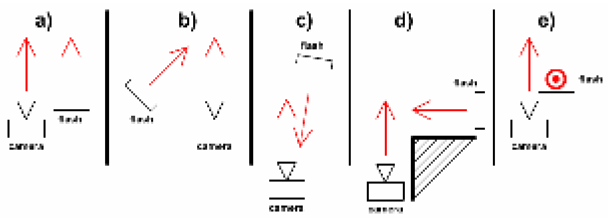
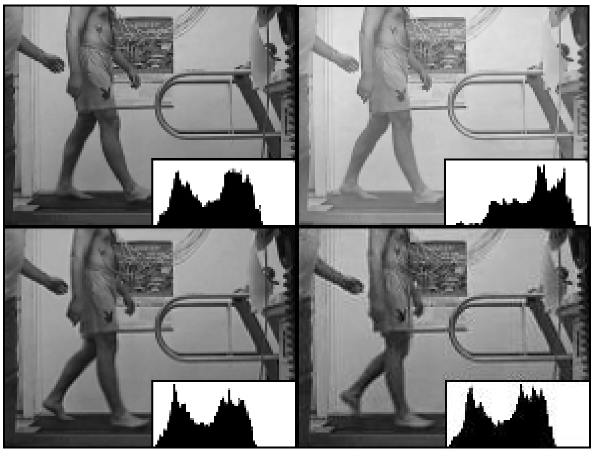
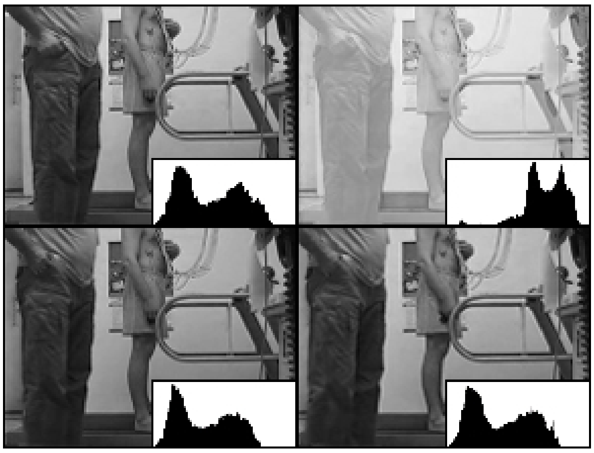


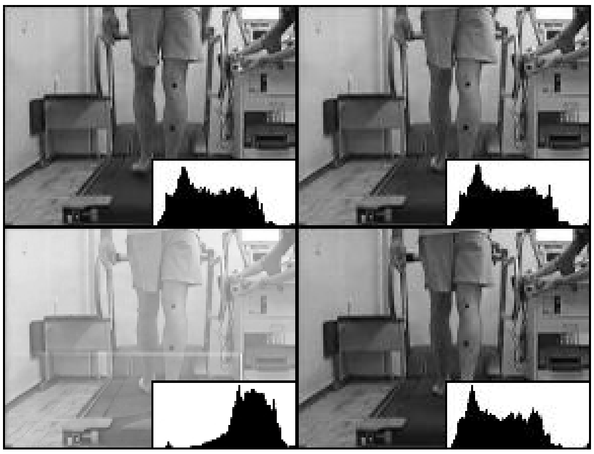
Figure 2: Mutual positions of a flash and a camera during synchronization experiments



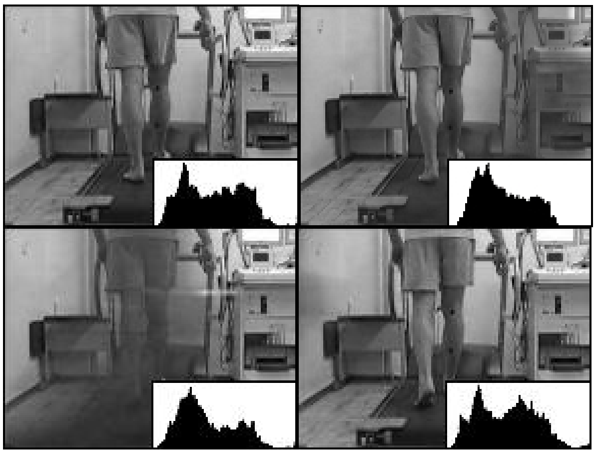
a



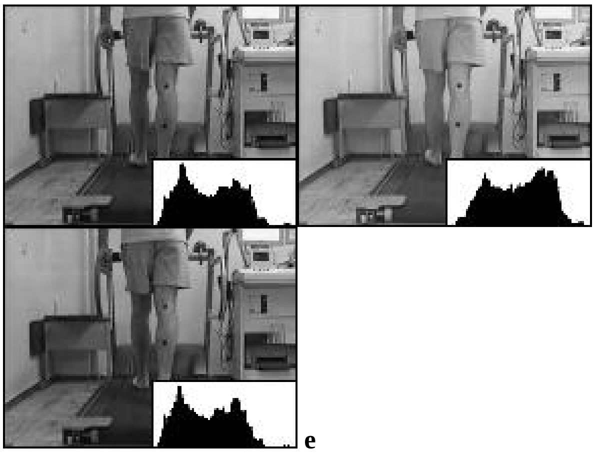
b



c



d



e

Figure 3: The frame sequences extracted from video taken during flash synchronization experiments

5 Segmentation

Segmentation is an important part of the process regarding the quality and accuracy of the result. We need to process the input image so we can allocate markers' centres that correspond to the joints locations as closely as possible.

The main object of our research in gait analysis is human lower extremity. If we assume naked leg, one way how to segment image is to use a *Skin colour model* [7], [8]. By using this model to the input image, we are able to differentiate regions that are skin coloured from the others. The main advantage of this model is its robustness and generality, because it is usable for all kinds of skin in various light conditions.

Hence, this skin colour model can transform a colour image into a grey scale image such that the grey value at each pixel shows the likelihood of the pixel belonging to the skin. With appropriate thresholding, the grey scale images can then be further transformed to a binary image showing skin regions and non-skin regions. [5].

In our case, usage of the model would not be so easy and straightforward, as we need to determine joints locations and not the position where foot (or leg) is located. If we want to secure the highest accuracy of foot joints location, then the alternative determination foot joints location directly from the foot skin regions is not very useful in this case.

5.1 Usage of Skin Colour Model

One way how to use the skin colour model is to consider the information that markers are placed on the human skin. This information could be useful for us in a situation, if we find the same coloured regions as used markers, which are not a part of scene. Whereas we are going out of fact that markers are placed on the skin, so the decision, whether region is or is not the marker, transforms to the region neighbourhood scanning. If a region (homogenous region consisting of pixels of colour which is in narrow interval around the marker colour) has in its neighbourhood pixels whose colour is determined as the colour of skin, it can be marked. Using this method we can reduce error percentage of region incorrectly detected as a marker.
Segmentation based on this principle can be done in two ways. The first way how to extract marker regions from the input image can be made as follows:

1) perform segmentation (the aim is to find all regions that are coloured with marker colour)
2) discover the region neighbourhood colour
3) if it is the skin colour, mark region as a marker
4) else mark region as a background

The second alternative is the algorithm, which comes out of the fact, that markers produce holes in the skin. The algorithm would have then the following steps:

1) segment skin regions from the input image
2) in this regions find inner regions that are not skin
3) mark this inner regions as markers

Problems

Each of these above methods introduces several problems. In the first case, there may be a problem that marker coloured regions must be segmented to have sharp borders with the colour of the skin. This means that between the marker and skin a ring of pixels that are not of the colour of skin or marker should not occur. This problem can be resolved by scanning wider neighbourhood of region, not just scanning pixels, that lies immediately beyond the border. Further we can consider usage of marker colour that is in sharp contrast with skin colour. In the second case, on the other hand, we have to find sub-regions of a region (markers on the skin), but we are looking for this sub-regions in smaller regions than the whole image.
The much more serious problem concerns homogeneity of the colour of human skin. During the gait relative positions of lower and upper part of an extremity are constantly changing. Lower part goes into the shadow alternately. So in this case one part of the skin seems to be darker and these dark regions need not be detected as skin using the skin colour model. This could be solved using the high-quality scene lightning or using close-fitting skin colour wear.

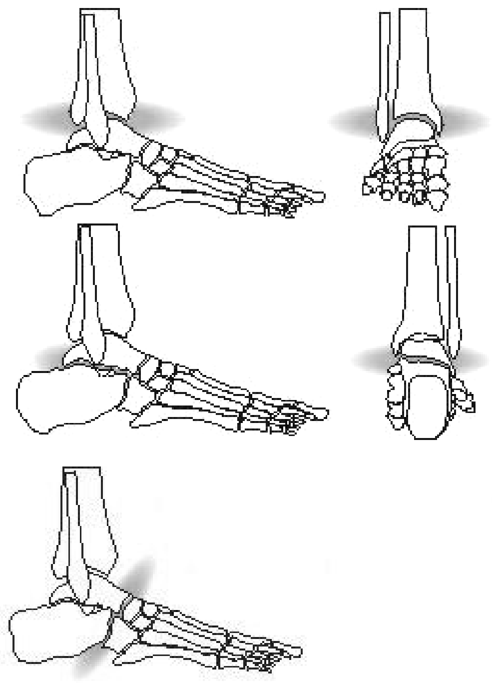
Alternative

Next alternative is to concentrate on finding just borders that belong to markers. The centre of a marker will be computed finally from points that create a marker border. So we need to find such points, which have their neighbourhood points (eight points around) both of skin colour and the colour of the markers. Not all of points found are points of marker’s border. Large amount of these points will create a leg contour. There are several methods how to decide that border is not a marker’s border. We can consider number of border points fitting into certain interval. Advantage of this method would be that we could directly compute the marker border from which we can easily compute the marker centre. On the other hand there is a risk of finding borders of objects that are not placed on the leg.

6 Animation and analysis

6.1 Medical background

Main object of research in this project is an ankle region. When we are talking about the ankle joint in orthopaedic slang we are talking about the joint that is positioned between calf bone (tibia and fibula) and the most top sole bone (talus). This joint is modelled as lower fibula and tibia parts create slice, which upper rounded talus flat fits into (Fig. 4a).



a) b) c)

Figure 4: a) ankle joint b) subtalar joint c) cross tarsal joint

This allows foot to move up (dorsiflexis) up to approximately +20 degrees above plane and move down (plantar flexis) up to approximately –50 degrees under gait plane.

Between two biggest foot bones (talus and calcaneus – heel bone) under and a little in front of the ankle joint there is placed so called subtalar joint (Fig. 4b), which is responsible for inversion (a move, that allows you to walk on foot edge) and eversion (inversion opposite). In normal conditions subtalar joint allows approximately 30 degree inversion and 15 degree eversion.

The third joint – cross tarsal joint (Fig. 4c) – is placed among two bone sets. The back side of this joint consists of talus and calcaneus bone. The front side consists of navicular and cuboid bone.

6.2 Skeleton model

The Skeleton in our model is represented as a tree structure (Fig. 5), where nodes represent objects which consist of bones (one or more bones). Each node can have several children. The rotation of any node causes every child of this rotating node to rotate with it too. There are defined rotation axes in each node. A pair of limiting angles belongs to each axis. These angles define range of motion in the given direction.

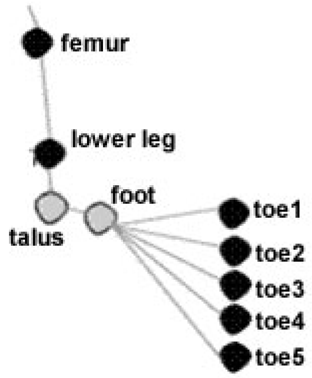


Figure 5: Kinematical chain of the skeleton model

Maintaining the aims of project it was important to define the axes of rotation in ankle around the talus correctly. We draw a conclusion that motion is best represented when foot rotates around the x axis and around the y-z axis (Fig. 6, Fig. 7).

For the most exact capture of this motion we had to choose appropriate arrangement of markers on the foot. As it can be seen in Figure 8, their concentration is the highest in the region of ankle joint.

To visualize the gait we need a model of both lower extremities starting at pelvis. Thus, we initially focused on searching another three dimensional models of the whole human skeleton (or just the extremities). The best of those models we found was the one of the VAKHUM project [9]. VAKHUM is a European project called *Virtual Animation of the Kinematics of the Human for Industrial, Educational and Research Purposes*.

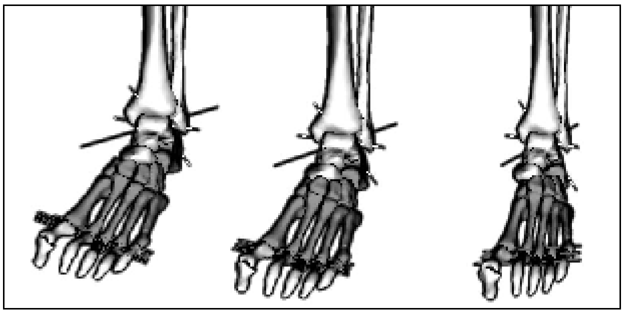


Figure 6: x-axis rotation of the sole, talus not moving

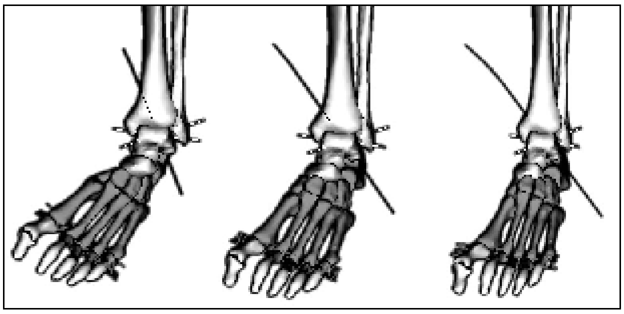


Figure 7: y/z-axis rotation of the sole, talus not moving

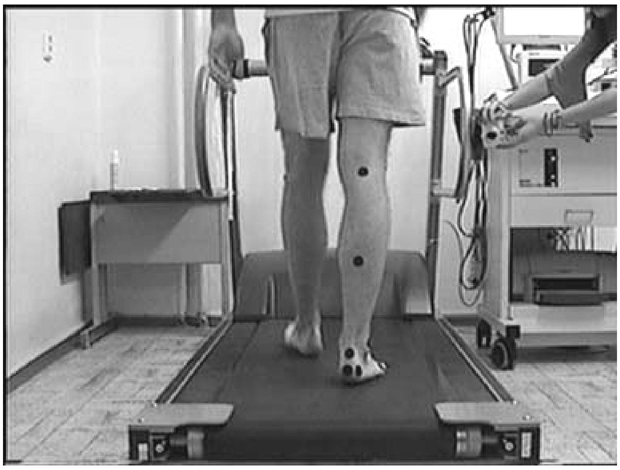


Figure 8: Segmentation markers attached on the lower extremity (rear view)

It aims particularly at the animation of human kinematics for the industry, educational and research purpose. The project focuses on picking and collecting data of human body structure and its kinematics, which would help the society to improve its education and activities. The project also deals, apart from data picking, with creating models and various tools for them. It is well-documented and everything is put free at one's disposal.

The model, as it was already mentioned consists of single bones or bone units, respectively. These rotate then around defined joints. The units used are as follows:

- pelvis (left and right half together; 2 objects, 2 992 vertices, 5 982 faces)
- femur (thigh bone; 1 object, 1 502 vertices, 3 000 faces)

- fibula, tibia and knee (3 objects, 3 005 vertices, 5 998 faces)
- talus and navicula (ankle bones; 2 objects, 1 104 vertices, 2 200 faces)
- metatarsal bones and the heel (12 objects, 5 674 vertices, 13 300 faces)
- toes segments (every toe separately; 6 objects, 1 737 vertices, 3 450 faces)

We exported the bone units independently into *.OBJ* format. Finally, the whole skeleton model consists of 50 objects, 29 036 vertices and 61 660 faces.

6.3 Visual analysis module

A visual analysis module is a separate application, which presents measured data from observed gait in graphs. It shows the time function of examined joints and time function of angular speeds between knee and toes in the ankle and between knee and heel in the ankle. Graphical interface of the application can be seen in Figure 9. The window of application is divided into two sections. The left section contains two graphs and the right one is serving for content configuration of graphs and work with them. In the graphs we can see drawn functions of spotted joints. The first graph shows dependency of altitude of spotted joint in time and the second one observes dependency of oscillation of spotted joints in a horizontal direction which is orthographic to the direction of motion. While the first graph is side view, the second one is top view. Each joint is drawn in different colour.

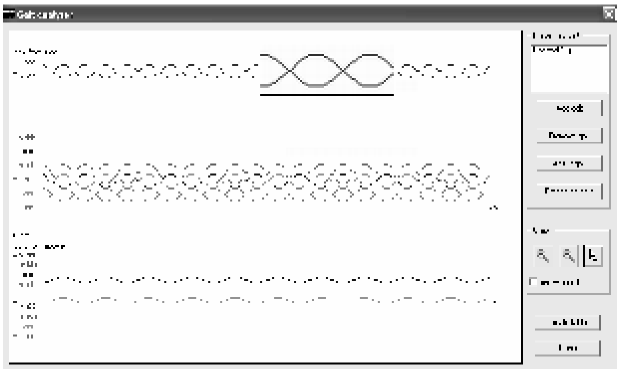


Figure 9: User interface of the analytical module (the data used in the picture are simulated)

There are gait graphs shown in the upper part that can be added or removed according to the user requirements. Each gait graph is represented in different colour. Depicted gaits graphs can be scaled and it is possible to adjust their positions in the graph. Shown points and angular speeds can be changed by the user in each graph separately. The graph can be zoomed in and out and cursors can be also inserted in the graph. It is possible to turn on the actual position shown in the graph as well. Measured data can presented also in the table.

7 Conclusion

In this paper we presented the current state of a project of human gait visualization. It is aimed to support orthopaedic diagnostics. The process of converting camera captured gait into animation consists of multiple steps. We have been concerning chiefly with synchronization and video segmentation and with the correct behaviour modelling of an ankle region of the skeleton.

We have successfully managed to analyse bones movements in the region of human ankle from physical and medical aspects. There is a little attention paid to this issue in the present research. In the field of synchronization we experimented with internal synchronization information using the flash impulses. This impulse serves for automated synchronization of video recordings taken with cameras recording the motion of a patient from aside and from behind (possibly from the front).

In the segmentation process we experimented with marker colours (on joints) and we evaluated the black colour as the most suitable under given conditions. The segmentation itself made by using *skin colour model* has not been proving good results in our (light) conditions. Nevertheless, it is generally possible to adjust the light conditions in the physician's office to make the use of skin colour model in human gait visualization thus more appropriate in the future. The stage of segmentation is followed by the conversion process of identified markers into three dimensional models. For this purpose it is advisable to concern with methods provided by epipolar geometry (three dimensional reconstruction of a scene represented by two or more projections; [6]).

We assume that usage of a high-speed camera can increase the accuracy of angular speed calculations compared with the conventional camera technology we have used so far. The low-end cameras dispose of 25 frames per second recording rate that corresponds to 40 ms per image frame. The angular velocities of joints appear to be partly out of the range in practice. It can thus have an impact on analysis of captured data and their medical signification. The analytical module based on orthopaedist's requirements is designed for two dimensions at present; however, with a deeper level of imagination we could project these data in three dimensional presentation.

8 Future Work

In the future, the motion of examined person should be computed and presented in real time. Then it will be possible to respond in more flexible way on observed defect of a gait and put it in the system before the physician starts to analyze examined motion with the module of visual analysis. This system may use then another, but more expansive synchronization (several synchronized and real time video grabbers) method.

With the current method of video grabbing and data transmission we did not need to solve some problems, which are to be solved in the case when we want to grab and represent data in real time. There can also be implemented other modules in the future, similar to related systems, which will provide the user not only the information about positions of joints and their angular speeds, but also about acceleration and other values that can be helpful from medical point of view. Also it is possible not only to concentrate on lower parts of a body but to analyze motion of all extremities and that of a body. For this purpose the model of skeleton must be implemented (and extended) and all relevant joints must be observed. This process extends demands not only for person observation but for segmentation of markers that are placed on the skin of a person too. It would be good to design such motion capturing methodology that can eliminate side effects and homogenous colour of the whole leg would be preserved.

We plan to implement the idea of superposition of more video sources. The one final goal of this project is an augmented reality system with an overlay of the captured gait video sequences and computer animated model of a skeleton that moves according to parameters of the ideal gait, eventually to parameters which represent any particular defected gait. This mixed reality image will represent the visual feedback with the goal to help patient in learning correct walking by matching both - real and animated sequences. The data gathered through captured gait can subsequently be used for educational purposes of next generation orthopaedists in the form of e-Learning materials.

9 Acknowledgements

The team working on this subject before us has moved a big step forward and we are sincerely grateful for their contribution. Our own analysis and design suggestions are particularly drawn from their documentation. Our enhancement concerning skeleton model kinematics would be only hardly so successful without having the work on the model already done. Further, our gratitude belongs to the orthopaedist MUDr. Vladimír Hostýn for presenting us the opportunity to work in his laboratory and educating us about medical background of the ankle kinematics. We wish to express our thanks also to our pedagogical supervisor associate professor Martin Šperka for his valuable thoughts and suggestions moving us constantly forward.

References

[1] Mareták, J., Matuška, M., Petreje, J., Sás, I.: Animácia a vizuálna analýza chôdze človeka. Team project, FIIT STU, Bratislava, Slovakia 2004.

[2] Charnwood dynamics Ltd.: Codamotion analysis http://www.charndyn.com/Products/Products_Software.html (November 2004) - Codamotion Analysis.

[3] Ariel Dynamics Inc.: Gait manual http://www.sportsci.com/adi2001/adi/services/support/manuals/gait/default.asp (November 2004) - APAS/Gait user manual.

[4] C-Motion, Inc.: Visual 3D https://www.c-motion.com/products/visual3d/visual3d.htm - Visual 3D system presentation (retrieved March 2005).

[5] Chang H., Robles U.:Face Detection - Skin Color Model http://www-cs-students.stanford.edu/~robles/ee368/skincolor.html (retrieved March 2005).

[6] Trucco E., Verri A.: Introductory Techniques for 3D Computer Vision – Upper Saddle River (USA) : Prentice Hall, 1998

[7] Gejguš, P., Šperka, M.: Face tracking for expressions simulations. In: B.Rachev - A. Smrikarov /eds./: Proceedings of the Int. Conference on Computer Systems and Technologies (e-Learning), CompSysTech´2003, Sofia 2003, pp. III-1-1-III-1-7.

[8] Sedláček M.: Evaluation of RGB and HSV Models in Human Faces Detection. Proceedings of the 7^{4h} Central European Seminar on Computer Graphics. TU Vienna and UK Bratislava, 2004. Pp. 125-131.

[9] VAKHUM project – Virtual Animation of the Kinematics of the Human for Industrial, Educational and Research Purposes http://www.ulb.ac.be/project/vakhum/ (retrieved January 2004).