TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

Faculty of Mechanical Engineering

Department of Mechatronics

Chair of Mechatronics Systems

MHE70LT

Irina Rubinshtein

Modeling movement of the lower human limbs by using IT Technology

Master's Thesis

Author applying for

master's sciences of technical

academic degrees

Tallinn
2016

AUTHORS DECLARATION

Hereby I declare that this Master's Thesis, my original investigation and achievement, submitted for the Master degree at Tallinn University of Technology has not been submitted for any degree or examination.

All works and major viewpoints of the other authors, data from other sources of literature and elsewhere used for writing this paper have been referenced.

Master's Thesis is completed under supervision of Mart Tamre

"......."....................2016

Author's

          ....   signature

Master's Thesis is in accordance with terms and requirements.

"......."....................2016

Supervisor's

          ....   signature

Eligible for defence.

Chairman of defence committee ....

"......."....................2016

          ....   signature

Irina Rubinshtein

Inimeste alajäsemete liikumise modelleerimine IT tehnoloogia abil

Autor taotleb tehnikateaduse

magistri akadeemilist kraadi

Tallinn

2016

AUTORIDEKLARATSIOON

Deklareerin, et käesolev lõputöö on minu iseseisva töö tulemus.

Esitatud materjalide põhjal ei ole varem akadeemilist kraadi taotletud.

Töös kasutatud kõik teiste autorite materjalid on varustatud vastavate viidetega.

Töö valmis Mart Tamre juhendamisel

"….."................... 2016. a.

Töö autor

....   allkiri

Töö vastab magistritööle esitatavatele nõuetele.

"......."....................2016. a.

Juhendaja

....   allkiri

Lubatud kaitsmisele.

.... õppekava kaitsmiskomisjoni esimees

"......."....................2016. a.

....   allkiri

TUT Department of Mechatronics

Chair of Mechatronics Systems

MASTER'S THESIS SHEET OF TASK'S

Year 2016 spring semester

Student: Irina Rubinshtein 158878MAHM
Curricula: MAHM - Mechatronics
Supervisors: Prof. Victor M. Musalimov, ITMO University
                       Prof. Mart Tamre, TUT

MASTER'S THESIS TOPIC:
(in Estonian) Inimeste alajäsemete liikumise modelleerimine IT tehnoloogia abil
(in English) Modeling movement of the lower human limbs by using IT Technology

Thesis tasks to be completed and the timetable:

Nr	Description of tasks	Timetable
1.	Technical literature overview. Investigation motion capture systems and software packages for motion simulation. Motion capture by means of Vicon system.	15.02.2015
2.	Processing of the data by means of Vicon system in software packages OpenSim.	01.03.2015
3.	Motion capture by means of Kinect system and the creation of models with the data obtained	20.03.2015
4.	Analysis of the model and data modeling for model features analysis.	15.04.2015
5.	Conclusions. Results.	16.05.2015

Solved engineering and economic problems: Solved engineering and economic problems: The aim of this Master's Thesis is creation of human movement patterns by means of data from motion capture systems. It's necessary for motion simulation capabilities a particular person and analysis of this movement.

Additional comments and requirements: …….…………………………........................

Language: English

Application is filed not later than 16.05.2015.

Deadline for submitting the theses 20.05.2015.

Student: Irina Rubinshtein   /Signature/ ………..   Date …………........

Supervisor: Prof. Mart Tamre   /Signature/ ………..   Date …………........

Supervisor: Prof. Victor M. Musalimov /Signature/ ………..   Date …………........

Confidentiality requirements and other conditions of the company are formulated as a company official signed letter

FOREWORD

The theme was issued by the Department of Mechatronics at the University ITMO. This topic interested me because currently the capabilities of motion capture systems are actively developing. Nowadays, there are few works that study the motion capture systems and the possibilities of movements modeling using them. In this regard, I believe that this topic is very relevant, and the solutions of the problems taken up in the work will help to understand better the capabilities of the motion capture systems and work with the models according to the data.

ACKNOWLEDGMENT

KOKKUVÕTE

Antud magistri töö oli kirjutatud „MSc Mechatronics Double Degree program between the Tallinn Technical University and St. Petersburg ITMO University" õppeprogrammi raamides. Professor Victor Musalimov, ITMO ülikooli Mehatroonika õppetooli juht, pakkus sellist magistritöö teemat. Valitud magistri töö põhiülesandeks on liikumise hõive süsteemi võimaluse uurimine ning liikumise modelleerimise võimalusi uurimine ja liikumise hõive süsteemi täpsuse analüüs.

Töö eesmärgiks on:
- eksperimendi-modelli lähenemise loomine kinemaatika ja dünaamika liikumise uurimiseks, kasutades liikumise hõive süsteemi ja tarkvara.
- uurimiste läbiviimise võimalus kasutades Kinect süsteemi, kallima süsteemi tüüpi Vicon alternatiivina.

Töö esimeses osas on liikumise hõive süsteemi ja liikumise modelleerimise kirjanduse ülevaade.
Töö teises osas on kirjutatud millised liikumise süsteemid olid kasutatud selles töös, ning milline algoritm oli kasutatud, kirjeldatud modelli loomise algoritm ning andmete modelleerimise programmide pakett.

Töö komas osa oli põhinenud loodud modelli analüüsile ning saadetud resultaatide võrdlemise teine teisega ja standart modelli OpenSimiga.

Kokkuvõttes võiks teha järeldusi, et antud magistri töös oli tehtud kahe liikumise hõive süsteemi töö võrdlemine, Viconi (markerbased system) ja Kinecti (markerless system). Nende erinevus on hindades ja objekti liikumise hõive tüüpis. Töö tulemuses oli loodud modellid programmi tarkvaras OpenSim ja tehtud modelleerimise tulemuse võrdlemine ning inimese skeletti liikumise analüüs, mis oli modelleeritud kahe süsteemi abil: Kinecti ja Viconiga võrreldes teine teisega ning strandard mudeli OpenSimiga abil.
Oli kontrollitud, et kallis statsionaarne süsteem Vicon on kergesti asendatav mobiilse ja odava Kinect süsteemiga alajäsemete modelleerimiseks ning nende liikumise uurimiseks. See annab palju uusi võimalusi mudelite loomiseks ning nende kasutamiseks mass segmentides.

ABSTRACT

This thesis was written in the course of the MSc Mechatronics Double Degree program between the Technical University Tallinn and St. Petersburg ITMO University. The head of The Department of Mechatronics of the University ITMO Professor Musalimov Victor offered the topic of this work. The main objectives of this thesis are to explore the possibilities of the motion capture systems, as well as the capabilities for motion modeling and the analysis of the accuracy of the motion capture systems.

The aims of this work are:
- creating of the experimental-model approach to study the kinematics and dynamics of human movement using the motion capture systems and software;
- study the possibility of using Kinect as a budget alternative to the expensive systems such as Vicon.

The first chapter is a literature review of the motion capture systems and analogues of the movement modeling.

The second chapter describes the motion capture systems, used in this work, the algorithm of the motion capture, the software packages for modeling the data and the algorithm for creating the model.

The third chapter is devoted to the analysis of the generated models and comparison of the results obtained using the motion capture systems with a standard model of OpenSim and with each other.

It can be concluded that in this work there was made a comparison of the two motion capture systems Vicon (marker system) and Kinect (markerless system), which distinguish in the type of object capture and the price category as well. As a result of this work, there were created models in the software package OpenSim and compared the results of modeling and motion analysis of the human skeleton, captured by two systems: Kinect and Vicon relatively to each other and the standard model of OpenSim. As a result, it was verified that it is possible to replace the expensive stationary system Vicon mobile with the cheaper Kinect system for research of movements of the lower limbs and modeling this movement. This, in turn, opens up new vistas for creating the models and uses them in the mass segment.

TABLE OF CONTENTS

INTRODUCTION

Currently, the motion capture technologies represent at once well-developed and still growing fields of science and technique. Up to date, these technologies have a very extensive scope of applications. The major task of the motion capture system is receiving, digitization and processing of digital data for an analyzed and animated object motion. The system operates in the following manner: an object (e.g. man or robot) is observed in dynamics by several cameras, and then the data from the cameras is delivered to the processing system where the system analysis occurs. Afterwards, the received intentional data transfers to the navigation and motion control system where it is imitated. [1]

The output of information is assumed to be implemented by the means of an animated three-dimensional model of a human being. The input of information can operate within the following method: generating expressions in a natural language in accordance with the analysis of reproducible gestures which are captured by the video capture motion technology.

In this paper, the video capture will be carried out by two motion capture systems Vicon and Kinect. Vicon is an expensive hardware-software complex of the 10 cameras at the field 5*5 m2, which makes it stationary, and where to capture data the object needs to put on a special suit that can hamper movement. There is also used a cheaper and more mobile Kinect system, which programmatically determines the object in space, builds a skeleton for it and there is no need for additional hardware.

The system analysis and simulation modeling (or animation) of a person by the medium of the capture motion technology gives huge advantages in the field of sports and others. New technologies are important in the fields of medicine, sports, cinematography, virtual reality systems, and automatic control. Nowadays theoretical and practical elaborations are in progress of the application of the following fields of medicine: orthopedics, recreational therapy, physiotherapy, pediatrics, neurology, psychology. In most fields of medicine motion capture is used at the capacity of tool for biomechanical analysis (the research of loads on parts of the body, such as muscles and bones, and movements that cause the loads, their roles in getting injured and sports and everyday achievements) and, in particular, gait analysis.[3]

1. THE THEORETICAL PART OF THE THESIS

1.1. Motion capture

Motion Capture or Mocap is the process of movements' recording with the possibility of transferring of the movements into a digital model.

For the first time the motion capture technology was developed in the late 70s, but it wasn't admitted as a revolutionary animation technique until the middle 80s. Initially, Mocap was tested by the military to capture the pilot's head movement by means of an electromagnetic transducer. Aside from the military research and development, Mocap has been integrated into clinical research. In biomechanical laboratories the analysis of human movements was carried out and also the assessment of the motion abnormalities in the following way: the similarity of exoskeleton was fastened to the human body. The analogue transmitted the signal of the angle change of joint bend.

The development of an actual, convenient and affordable non-contact man-machine interface requires the use of technologies that can provide these attributes. Most prospective technologies in this direction are those which evolve in the motion capture systems. It's necessary to analyze all the existing motion capture systems to determine the most appropriate hardware solutions and to develop the effective control algorithms. There are two main types of the motion capture systems: the marker ones, which require special equipment, and the markerless capture system. [6]

1.2. Marker systems of the motion capture technology

In the markers systems of the motion capture technology the performer puts on a special suit with sensors, conducts certain movements, strikes agreed poses and executes some movements. The cameras capture the data from the sensors. Afterwards the data is transferred to the computer. There an integrated three-dimensional model of human movements is formed. On the basis of this model in real-time processing (or later) the animation of a digital character is created. The same method is used to reproduce the facial expressions of actors (for this purpose, the markers are fixed on their faces; then the movements of facial muscles are detected). A great amount of the marker systems of the motion capture technology is developed to date. They

differ   in   the   principle   of   the   movements   transfer.
The existing marker systems of the motion capture technology differ in the principles of
movements tracking. According to this, the following systems are identified: passive optical,
active optical, magnetic, mechanical and gyroscopic system. [33]

1.2.1. Passive optical systems

The set of the system includes the suit with the makers. The markers themselves do not light;
they only reflect light, that's why they are called "passive systems".

The disadvantages of the passive systems:
• The markers establishment takes up a lot of time;
• The system can mix up the markers due to the rapid motion or close spacing (the identification
of each marker separately is not provided). [33]

1.2.2. Active optical systems

In the systems LEDs are used with radio synchronization and onboard processing instead of the
retro reflective markers which are attached to the performers' suit. Each LED gets an identifier
(to detect accurately the ID markers), and to recognize them after the overlapping and the
camera emergence within the eyeshot.

The disadvantages of the active systems:
• It's impossible to capture movements and facial expressions;
• An additional controller, which is attached to the performer's suit, hinders their movements;
• High cost of the hardware components and low reliability. [33]

1.2.3. Magnetic systems

In this case, the marker-magnets are used for motion capture, and the receivers are used as
cameras. The markers positions are calculated by distortion of the magnetic flux.

The disadvantages of the magnetic systems:

• The susceptibility to magnetic hum and electrical noise from metallic objects and surroundings;

• The dependence of the sensors' sensitivity from their relative disposition;

• The high costs of the markers.

• The smaller size of the working area, in comparison with optical systems.

• The additional wires leading to the computer, and controllers that are attached to the performer;

• The impossibility of using the system to capture facial expressions. [33]

1.2.4. Mechanical systems

For gathering the motions' information the performer puts on special equipment – the skeletal-like structure which repeats all the men movements. At the same time, the information on the joint angles of the human body is sent to the computer.

The disadvantages of the mechanical systems:

• High probability of the exoskeleton mechanics incapacitation when using it for a long time;

• The impossibility of the motion capture systems' operation, if some performers participate in the process or it's necessary to capture the movements on the floor;

• The inability to capture the facial expressions.

• The mechanical skeleton, hindering the performers' movement, represents a structure with a large number of wires extending from the structure to the computer. [33]

1.2.5. The gyroscopic / inertial systems

For gathering information on movements the tiny gyroscope and inertial sensors, situated on the performers' body as well as the markers or magnets of the others systems are used. The computer receives, then processes and stores the information from the inertial sensors which can be used to recover the sensors' positions in space and their relative orientation.

The disadvantages of the gyroscopic/inertial systems:

• The impossibility of using the system to capture facial expressions;

• The high costs of the gyroscope sensors;

• A large number of wires extending from the human body to the computer. [33]

1.3. Markerless motion captures systems

The markerless technologies do not require special sensors or suit. They are based on the technologies of computer vision and image identification. Thereby it is possible to detect and track human movements in informal clothes. It extends the range of applications of such systems. The development of three-dimensional animation is essentially simplified: preparations for the shooting gather pace and there appears the possibility of motion capture (e. g. fighting, falling, jumping, etc.) without damaging the hardware modules of the system. Nowadays, there are a limited number of the markerless systems, which are appropriate for practical application, although the intensive researches in the field are conducted since the middle 90s. User software for the markerless motion capture allows going without special equipment, special lighting and properly organized space. At the moment it is possible to distinguish two types of the markerless systems according to the type of the used sensors which are color cameras and sensor rangefinders. [33]

1.3.1. The markerless systems based on color cameras

In the markerless systems based on color cameras the motion capture occurs with the help of a usual optical camera and a personal computer. The example of such system is the product of the company *iPi Soft*. The software *iPi Motion Capture* uses images as input data, obtained from some cameras which are situated in space in accordance with the spacing chart.

The motion capture doesn't happen on the real-time basis. It happens on the basis of processing of obtained data. Thus, the process of motion capture involves two stages: shooting and object recognition on the received video sequence. Thereby there are some significant demands on shooting case: steady light of sufficient intensity; there shouldn't be foreign objects within the field of camera view. In addition to this, in the beginning of the shooting the performer has to strike a standard pose for detecting the key, reference positions, used for tracking. This type of systems is aimed at establishing the basis for the three-dimensional animation, but not for non-contact control. [33]

1.3.2. Markerless systems with the sensor-rangefinder

This is the second type of markerless motion capture systems for movements' recognition which is based on analysis of data from the sensor-rangefinder (one or more). A similar solution is implemented in the following software: *OpenNI*, *Kinect SDK*, *iPi Soft*, etc. The use of the sensors-rangefinder allows simplifying a number of key tasks for computer vision used in markerless motion capture systems, i. e., the clipping of the background and image segmentations. As consequence, these solutions are less resource-intensive and allow executing motion capture in a real-time mode. In addition, the use of rangefinders reduces the number of cameras during the process of motion capture. At the heart of these systems there is the image analysis, including recognition and tracking of individual objects of the obtained image of the human being (head, shoulders, elbows, hands, knees, and feet). [33]

Let's consider the features of several solutions for users' motion capture on the basis of the analysis of data from the sensor-rangefinder. In *OpenNI* it's necessary to hold the initial standard pose of the performer for motion capture. Due to the fact that the human body shape is unique, the calibration process of each user (the search of points on the reference position) takes different time. The calibration time can vary in a few seconds. It shows noticeable dependence on the anthropometric data of body surface area of different users. The strong-built people are calibrated much faster than the delicate-built people. The algorithm, based on the use of standard poses, recognizes the user by using simple comparison. The next step is body movements tracking on the basis of the tracking methods. The main idea of this group of algorithms involves the following stages: if there is an image area in the first frame, which is detectable like an arm, then on the next iteration the object (the arm) cannot move far enough away in comparison with the previous iteration. Consequently, only nearby regions can be detected. The tracking algorithms allow achieving good results when following ideal conditions, but in practice, they may fail except for described above calibration problems. The lost position of the body for any reason can be an example in this situation. The algorithms do not provide proper solutions of the problem in terms of the necessary allocation of the detected object among other objects or items coming to the foreground, even for a short period of time. It is also difficult to organize the reliable tracking of two or more people. All the above mentioned features make significant limitations for the use of the software in non-contact control. [21]

Another solution was proposed by *Microsoft* in the software product *Kinect SDK*. The basis of the product was the software and hardware application of the game console *XBOX360* with the use of *Kinect*. Let's consider the general principles of this approach. To remove the constraints peculiar to *OpenNI*, in the system of *Kinect SDK*, in addition to the tracking algorithms, it's necessary to apply the local analysis of each pixel to identify the users' body parts. Traditional object recognition (e. g. expert systems, perceptrons) uses the decision-making structure, which is trained on many samples. To ensure its work the classifier with a large number of characteristic, which have to include information used in the detection of 23 different objects, is provided. In most cases, one of the most difficult tasks is to identify informative features. All the features are formulated with the use of following values:

$$f = d(x + u/d(x)) - d(x + v/d(x)) \hspace{3cm} (1.1)$$

where: u, v are two vectors of translation,
d(x) is the depth of pixel, i.e. the distance from the sensor to the point whose projection on the image plane corresponds to the pixel x.

Note that the translations are standardized by the depth of the source pixel d(x). The values of f(x, u, and v) allow us to numerically measure features of the pixel's three-dimensional surroundings. The main stage of the system development was the classifier training, known as "Random Forest". Each tree was trained on a set of features derived from the collection of images of the depth manuscript. Moreover, these features characterize a certain body part on the depth manuscript received from the sensor. The trees' training was iterative and lasted for as long as they did not produce the correct identification for a particular body region on the test image collection. The trees' training is a resource-intensive task. For example, the training time of three trees on the 1000-core cluster with 1 million images takes up more than 20 hours. The trained classifiers determine the probability of an implement of an image element to a particular region of the body. The next stage is the selection of regions with the maximum classification probability of the body area. In particular, the region will be defined as "foot", if the trained tree gives the maximum probability for this ares. The last stage is the determination of the probable joints' position between the areas which are recognized as the body parts. For the user's tracking possibility for body turnings the algorithm was trained on the Forest consisting of 900 thousand images. In addition, this algorithm allows conducting simultaneous tracking of

multiple users in the frame. The algorithm was implemented by Microsoft Research on GPU with the ability of classification of the body parts. The GPU XBOX360 allowed carrying out the computation of iteration for 5 msec. The same algorithm for iteration on the modern eight core processor is implemented during about 20 msec. [21]

The opportunities of the sensor-rangefinder for non-contact interface development.

Currently, there are several types of the sensors-rangefinders:
1) Stereoscopic cameras. They allow obtaining the depth manuscripts using two usual cameras. The advantages: low costs, high availability on the market. The disadvantages: high computational resource intensiveness, high level of dependence on illumination.

2) Stereoscopic camera with the structured infrared lighting. The advantages: high accuracy, low costs, low computational resource intensiveness, low dependence on the illumination level. The disadvantages: low availability on the market, low accuracy at distances over 2 meters.

3) TOF-camera (Time of Flight). The advantages: high accuracy, high availability on the market, low computational resource intensiveness, no dependence on level of illumination in most cases; high range of coverage relatively to the other types of the sensors-rangefinders. The disadvantages: high costs.

On the basis of the sensors characteristics' comparison it may be concluded that for the development of non-contact interface the TOF camera is more preferable. Among the existing TOF cameras may be mentioned *Panasonic D-imager, Prime Sense, Asus Xtion, and Kinect.* Based on the criteria of availability on the market, low costs, the availability of open drivers and libraries; it's convenient to focus on the sensor Kinect which is well-developed. In addition, this hardware for a long time was the only offer in this class of devices.

1.4. Analogues

1.4.1. Human jaw as an example of the use of *OpenSim* in closed contours

The software OpenSim represents an analysis tool for the musculoskeletal systems, which gives powerful means of analysis: kinematics, changes in the muscles and tendons length with the course of time, changes in the brachial muscle strength, etc. However, the main disadvantage of *OpenSim* appears in the processing of closed contours. It is present in this case, since the mandible is attached to temporal bones with two temporomandibular joints. The conclusive idea lies in the fact that the user should write their own motions' equations, and not to use the dynamics processor of the *OpenSim* package. Finally, the OpenSim results are encouraging; however the model is very sensitive to the attachment points of muscles and physiological properties of muscles. In addition, the results of inverse dynamic problems solving are not reactions, operating upon on the joints, but the closing forces and moments, representing the sum of all forces and all moments, operating on the joint. It's necessary to record the electromyogram simultaneously with the recording of the mandibles kinematics to validate the represented model.

By default, *OpenSim* uses right-handed coordinate system. The model was defined so that the axis X passed in the anteroposterior direction, the axis Y passed in the craniocaudal direction and the axis Z - in the mediolateral direction (fig.1.1.). The Skull and maxilla were restrained, and only the mandible was free to move.
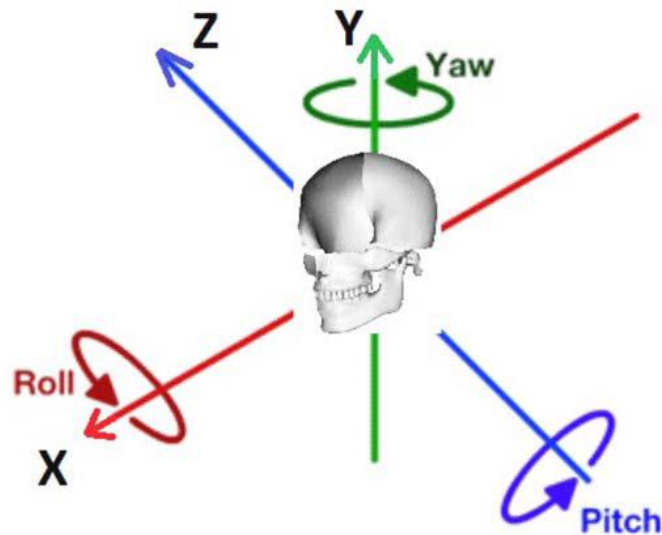
Figure 1.1. Right-hand coordinate system in *OpenSim*. The X-axis is dorsoventral (positive direction is ventral); the Y-axis is craniocaudal (positive direction is cranial); the Z-axis is mediolateral (positive direction is from the left to the right in relation to the individual). Rotation index marks: roll, pitch, yaw, relatively to the axes X, Y, Z.

Both TMJs had six degrees of freedom. Change range for all the degrees of freedom (rotations and translations): pitch (opening of the mouth, rotation about the mediolateral axis) is 30°; roll (rotation around the dorsoventral axis) is ± 3°; yaw (rotation around the craniocaudal axis) is ± 3°; lateral excursion is ± 9 mm; protrusion is 7 mm, retrusion is 1.5 mm; recession is 5 mm. For each side of the head five muscles were divided into 11 parts: superficial masseter muscle, deep masseter muscle, intrinsic wing muscle, inferior external wing muscle, superior external wing muscle, anterior temporal muscle, middle temporal muscle, posterior temporal muscle, geniohyoid muscle, anterior mylohyoid muscle, posterior mylohyoid muscle. For each muscle there were determined several physiological properties: optimal and maximum length, cross-sectional area, maximum isometric force and pennation angle. In addition, three correlations that determine the magnitude of the arising forces were defined in *OpenSim* by default (the force in tendons – tendon length, the active force – fiber length, the passive force – fiber length). It was assumed that the muscles go straightforward between their attachment points. For the muscles that bend to the joints or bones there can be defined intermediate points. First of all, the test person was asked to compress the force sensor placed between his anterior premolar to the maximum within 1 sec. Then he was asked to open the mouth maximally and close slowly. The whole cycle lasted for 2.5 sec. The LEDs for the movements' recording were located on

the right side of the head to avoid crossing with the force sensor's wire on the left side. The compression force preceding the start of mouth opening was measured with the use of one-dimensional piezoelectric probe of force. The probe was placed between the left premolars. The force sensor was working in the range from 0 to 500 N.

The disadvantage of *OpenSim*, detected during the modeling, is that it is not able to directly model a closed loop. It means that the bones are connected in such way that they form a close looped kinematic chain. The mandible attached to the skull is an example of such chain. In *OpenSim* at determining the joint it is said that every part of the body is attached to the parent body with only one joint. Therefore, to test *OpenSim* as a tool for biomechanical analysis of the masticatory system, the research was begun with the model with a single joint, i.e. there has been determined only the left TMJ or only the right TMJ. Then, in order to obtain more realistic results, there was simulated the system with two TMJ. For this the mandible was divided into the left and the right parts. Each part was attached to the skull with its own TMJ. There was set the limitation that prevented the separation of the two parts of the mandible. As the developers stress, *OpenSim* is a platform where community of biomechanics can build the library of models which can be used to share, test, analyze and improve through comprehensive cooperation. Commercial product such as *SIMM*, *Visual 3D (C-Motion Inc.)*, *Anybody (Anybody Technology)* or *Adams (MSC Software Corp.)*, do not provide complete access to the program source code that causes interference to the researchers working in the field of biomechanics with enhancement of their capabilities. The *OpenSim* developers also claim that the plug-in technology allows developing customized controllers, analytical estimation, contact models, and muscle models. Unscaled model of the whole body, by default generated in *OpenSim*, is based on the individual with the growth of approximately 1.8 m and the weight of 75.16 kg. This generated model can be scaled to anthropometric data of the test person. The problem is the accuracy of the scaled model in comparison with the model, based on magnetic resonance imaging (MRI). As for the scaling feature in *OpenSim*, the various scaling methods (uniform scaling, non-uniform scaling) had minor effect at determining the efforts in the hip joint (personal communication). Even though there are several models of various body parts (hand, head, neck, lower limbs, etc.), they cannot be simply combined to form more complex model, e.g. the model of the entire human body. Each model is aimed at studying a particular problem (kinematics analysis, dynamics analysis, static optimization, etc.). And if users forget about these limits, then they can improperly interpret the results of the use of their own models. That is why the developers propose to use a simple but more detailed model of some interesting

structure (muscle, joint, etc.) instead of using a model of the whole body, but less detailed one. Finally, users have to remember what the model was intended for. The most common mistakes of novice users of OpenSim while kinematic analysis or inverse dynamic analysis are that: 1) for individual parts of the body the mass moment of inertia is not defined; 2) the isometric force defined for certain muscles, cannot meet requirements of the speeds and accelerations that match to prescribed motions; 3) for some degrees of freedom muscle appear to be undefined. However, the results of the inverse dynamic analysis in *OpenSim* are "closing force and rotational moments", i.e. the sum of all the forces and all the rotational moments operating upon the joint, not the reactions appearing in the joint. The represented study was aimed at the solution to the question whether public-domain software *OpenSim* matches to the masticatory system analysis. It turned out that *OpenSim* is a powerful biomechanical tool which is easy to use. There is also one serious disadvantage of its use for the masticatory system analysis, appearing in the processing of closed contours. The kinematic analysis' tools in *OpenSim* give us powerful instruments both for the kinematics analysis (linear and angular speeds and accelerations) and change the muscles and tendons length with the course of time as well as shoulder muscle forces in relation to the joint, etc. These instruments can be used as input information in the user's equations of motions and in his own procedure for static optimization. Apparently, this procedure (the combination of *OpenSim* and, for example, *MatlabTM*) is a promising tool for the processing of complex mandible's movements. In the research there was modeled the mandible while using two different approaches: 1) the mandible was connected to the skull by one joint; 2) there were used both TMJs while modeling. The model with one joint, in essence, is an oversimplification of the actual anatomy and therefore gives only approximate results. The results of the second model are more promising; however, the model is very sensitive to the attachment points of the muscles and physiological properties of the muscles, so one should take care of their non-contradiction. In addition, the results, obtained in *OpenSim* in the inverse dynamics problem (forces in the joint), differed from the expected ones. But these results are "closing force and rotational moments", which are the sum of all the forces and all the rotational moments operating upon the joint and not the reactive power. This may explain the differences in the results. [10]

2. THE PRACTICAL PART OF THE THESIS

The aim of this thesis is creating an experimentally-model approach to study the kinematics and dynamics of human movements with the use of the motion capture systems and software.
In my work I used the marker and markerless motion capture systems. The marker motion capture system was the *Vicon* system, and the markerless one was *Kinect*. [11]

2.1. Vicon

Vicon produces equipment and software on special purpose for three-dimensional optical marker motion capture systems. The system operation principle is based on the combination of three-dimensional visualization with the method of quantitative gait analysis and electromyography.

The type of this system is the marker optical system.

The *Vicon* system consists of 10 optical cameras, infrared transmitters and a binding server, which analyzes and transmits the data to the computer where the program Vicon Blade conducts parameterization, recording and processing of data. The performer puts on a fitted suit made of Velcro fabric to which the reflective markers are attached. The transmitters project the infrared rays in the capture area; the cameras take the reflected rays and determine the position of markers in space.

The areas of application of this system are animation and film industry, installations and entertainment, sports medicine and education, engineering and robotechnics, biomechanics and zoology.

The advantages of this system are high capture's accuracy, powerful data post-processing, and flexibility of the system integration with different number of cameras.

The disadvantages of this system are time-consuming work, although the possibility of the system's transportability.
The technical bases for the system operation are infrared cameras that allow recording movements at the rate of 200 frames per second. They get information from special reflective

sensors-markers that are attached to the human skin in a specific sequence. It is worth saying that the number of these markers and their location are of essence for the pursuance of the research. There are several computer systems that allow carrying out the gait analysis. The computer-measuring motion capture systems *Vicon* (UK), *Elit* (Italy), etc. are the first among the computer systems. In Russia the analogue of such systems is the complex *Biomechanics* of the domestic firm MBN.

The scientists all over the world continuously develop and improve the skeletal form of the markers location. For example, one of the most widespread models is *KAD* (*Knee Alignment Device*). Generally, it is used the United States' laboratories. Another famous model is the *Oxford foot model*. It was developed by the scientists from Oxford University. The model is based on the use of 48 markers attached to the men lower limbs of man with special plug-magnifiers. This model is preferable when someone works with children of preschool age. Different laboratories working with gaits' analysis choose the models as they wish. The software *Vicon BodyBuilder*, in particular, allows independently developing one's own skeleton form to conduct the necessary research. The powerful mathematical apparatus allows creating a schematic skeleton (pseudo-skeleton) and considering in details and researching any movement on the 3D display. This gives the opportunity of simultaneous capture and analysis of several performers or other objects of study. [4]

2.2. Description of shooting

Before the shooting the cameras have to be calibrated. For this purpose, the special calibration wands are used. The calibration process helps the cameras to determine their position in space relatively to each other, and learn where the floor is situated. With the course of time there appears inaccuracy in the calibration data. It is necessary to conduct recalibration.

After the system is calibrated and the markers are attached to the performer, it is essential to calibrate him. For this purpose, under the cameras he needs to do *ROM* or *Range of Motion*. According to the obtained data, there appears a subject in the program *Vicon*, while the system operator deals with the processing of the subject. The record is kept in the format X2d, which is processed in *Vicon IQ*. The markers are also attached to the additional items that are used by the performers in the animations. Relying on the markers, it is possible to track the object's

movements in *Motion Builder*, and to get, as a result, its realistic animation. The output data can be in the format of TRC, FBX, and BVH.

The TRC format carries information about the markers' movements and in the processing in *Motion Builder* it provides a range of tools to improve the quality.

The FBX format can have different visualizations: The file can include data resembling the TRC format, but without the possibility of the markers debugging and can include a fully-animated model or several models.

The Filmbox format can be easily imported into *3D studio MAX* and *Maya*.

The BVH format is used only for the export of the Mocap data on the animation module skeleton of *Character Studio* for *3D studio MAX*.

2.2.1. Vicon Cameras

The *Vicon* technology bases are the cameras are of self-design project.

Fig. 2.1. Vicon camera

The *Vicon* Company offers the optical cameras *Bonita*, which are intended for the motion capture. The camera is cross functional and affordable solution for the motion capture process in small fields and in the virtual reality surroundings to capture facial expressions.

The small size (122x80x79 mm) and weight (0.3 kg) of the camera Bonita allows placing it on any platform, using standard bends for photographic utensils.
Bonita is a unique balance of cost and functionality. For the first 90 days of release there were sold over 150 cameras.

2.2.2. Vicon BLADE

Vicon Blade is a flexible and scalable platform with plug-in architecture, a complex set of management tools and full-function source scripting language HSL. One of the best motion capture systems is a software pack for MoCap which is a comprehensive solution that offers all the necessary tools to digitize the motion of an object with the use of the markers, which are attached to the object, cleaning and retargeting in real-time within integrated surroundings with high accuracy.

The software *Vicon Blade* maintains control for the Vicon cameras, the processing of 2D data from the cameras and the reconstruction of the 3D space. It also allows creating kinematic models of biomechanical objects, processing of the obtained data, exporting the data for further processing, and catalogizing the data. It supports distributed batch processing of data as well as data export including the FBX and C3D formats. [27]

Powerful tools of kinematic miscount and retargeting

At the disposal of Vicon Blade there are the latest algorithms of kinematic miscount allowing to optimize the data processing and to achieve the desired results as soon as possible. The use of these algorithms for retargeting allows significantly increasing the transmission efficiency for the skeleton forms of any shapes and sizes. To achieve an absolutely accurate display of the captured object one is given the complete control over the process of digitization.

Scalable system for real-time operation

The flexibility of the system *Vicon Blade* allows driving it to specific requirements for digitization: it is always possible to choose the optimal configuration, not overloading the system and, in addition, which allows realizing creative concepts comprehensively. *Vicon Blade* allows capturing the 3D data in real time and the 2D data in full resolution for further processing.

Today *Blade* is in the top of applications for the optical motion capture. It includes a complete set of tools, interfaces, algorithms and libraries to implement a full cycle of motion capture - from camera setting to cleaning and data export.
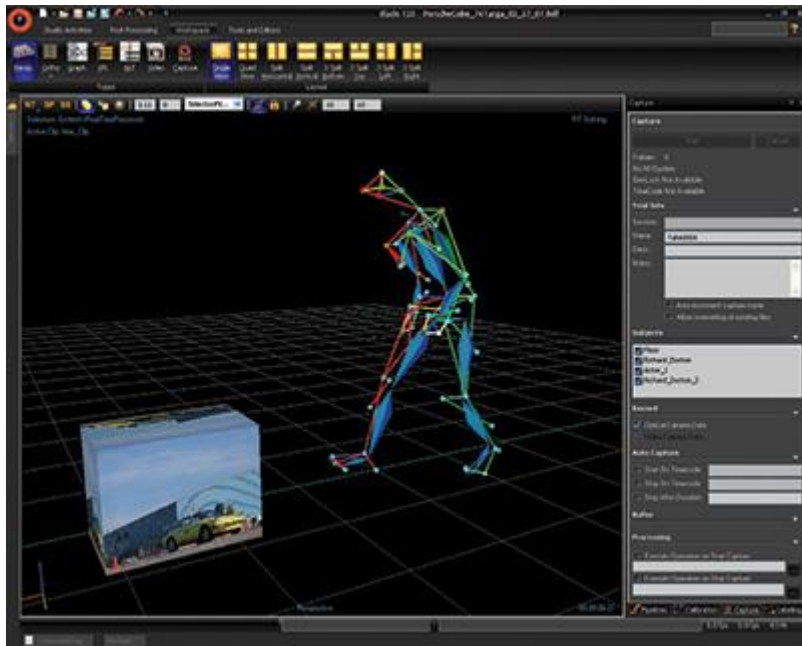
Fig. 2.2. The example of the operation of *Vicon Blade*

2.3. The Kinect System

The markerless motion capture system that I used was the Kinect system. The technology description: device of small size, consisting of an IR projector transmitting the infrared radiation, an infrared receiver, optical camera and chip, which was developed by the company Primesence, that allows recognizing the objects' and peoples' movements in three-dimensional space. The device projects infrared rays and receives them back, analyzing the time spent on the ray path, and thus, building the image depth manuscript. For the body's mocap it is necessary to observe the minimum conditions: unglossy fitting clothes, sufficient distance from the sensor and the performer's absence in the first frames of the recording.

The advantages: the technology availability, the system's mobility, free software development, the ability to connect 4 sensors simultaneously.

The disadvantages: very relative accuracy of the obtained data, jerking and scrolling of limbs, limited range of possible movements when capturing with the use of one device. [28]

The Kinect story, which was called Project Natal during development, was launched in November 2010, when the first generation of this unusual device has become available as an accessory to the Xbox 360 gaming console, which mounted on top of TV or in front of it.

Fig. 2.3. The Xbox 360 gaming console

Kinect could replace the standard controller of the gaming console that allows managing specially adapted games through motions and voice, and as distinguished from *Wii Remote* or *PlayStation Move*, the user does not need to keep in hands any controllers.
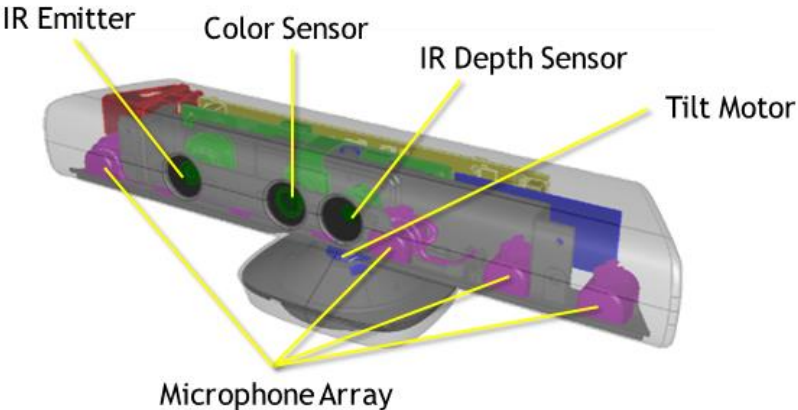
Fig. 2.4. Components of the Kinect sensor

Structurally, *Kinect* is presented in a horizontally located rectangular case with a small round base. The sensor is usually located above or below the display. Dimensions: the length about 23 cm and the height 4 cm. It consists of the depth sensor, color camera and microphone array. The Kinect SDK software, supplied in the set, allows realizing three-dimensional tracking of the user's body, identifying facial expressions, recognizing the voice. The microphone array of the Xbox 360 sensor produces a localization of the sound source and accomplishes the noise reduction that gives the opportunity to talk without the headphone and microphone *Xbox Live*. The depth sensor combines an infrared projector and a monochrome CMOS-matrix

(*complementary metaloxide-semiconductor*). This combination allows the Kinect sensor to obtain three-dimensional image in any natural light. The Kinect sensor was originally based on the Microsoft software and the webcam *ZCam* released in 2000 by the firm *3DV Systems*. ZCam is a variation of the TOF-camera, which allows obtaining three-dimensional video information. The main components of the sensor are shown in the figure 2.4. IR Emitter is an infrared searchlight. It is used for emitting infrared rays that reflect from objects and fall directly on the IR receiver. [29]

IR Depth Sensor is an infrared receiver. It gathers the reflected rays, converting them into the distance from the sensor to the objects. There forms the distance matrix – an image with a resolution of 640×480. The infrared receiver transmits the received distance values with a frequency of 30 Hertz. *Color Sensor* is a color camera used for capturing videos with the maximum resolution of 1280×720. The viewing picture angle of this camera is 43° vertically and 57° horizontally. The image format is RGB or YUV. *Microphone array* is an array of microphones. 4 microphones provide the determination of the sound source's location and the direction of sound waves. The onboard processor of sound processing accomplishes the function of echo suppressing and noise reduction.

Tilt Motor is a servomotor of adjustment of the sensor's pitch angle. It allows programmatically changing the angle in the range from -27 to +27 degrees vertically. Logging of the sensor on to the PC is accomplished through the USB-port. It is possible to logging on to 4 sensors. A significant feature of the sensor's hardware is the range of working distance of the depth sensor, whereby it is able to get three-dimensional information about the visible objects.

Default Range is available for the operating of the depth sensor for *Kinect* (Xbox). Another important aspect of the hardware is the range of working distances, i.e. what distance the sensor is able to see objects at (finder's data). Again, the picture helps to demonstrate the capabilities of *Kinect*.
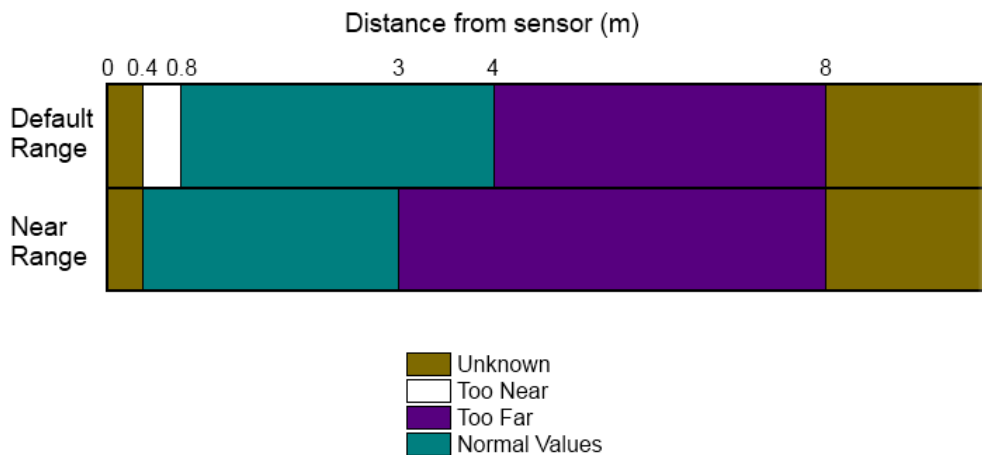
Fig. 2.5. The range of working distances of the sensor

Here is a simple example: for all the objects in the frame within Normal Values the sensor will return the measured distance, but for the objects beyond this range, the sensor will return either zero, or a defined constant for each range (it depends on the constrained settings).

The three-dimensionality of the data received from the Kinect sensor allows effectively detecting the user's hands and fingers with minimal compute resources due to the possibility of objects segmenting and the background clipping taking into account their mutual location in space.

2.3.1. How the Kinect technology works

Kinect tracks the human body. In this case, there used a classical technique for pattern identification, but which is implemented in the modern ways. The device that tracks the position of the body, existed in the past, but their main problem was the need for a user to become in a standard position in which the algorithm recognizes him with the use of simple comparison. After the tracking algorithm, following for the body's movements, is used. The main idea was: if in the first frame there is an area identified as an arm, then in the next frame the arm cannot move far, and so, the nearby areas are identified. The tracking algorithms are good in theory, but in practice they fail, if the body position is lost for some reason; they mishandle with other objects that enclose the tracked person, even for a short time. In addition, the tracking of multiple people is difficult; and when the track is "lost", it is possible to restore the track after quite a long time, if it is possible at all. The developers returned to the underlying principles and decided to build a system of the body recognition,

which does not depend on tracking but finds the body parts, basing on the local analysis of each pixel. The traditional pattern recognition works by using of decision-making structure, trained on multiple samples. To make it work, there is usually given a classifier with a large number of characteristic values that contain the information necessary for the object's recognition. In many cases, the task of informative features selection is the most difficult one. The chosen features are simple and not obvious in the sense of information content for identification of the body parts. All the features are obtained from the following formula:

$$f = d(x + u/d(x)) — d(x + v/d(x)) \qquad\qquad (2.1)$$

Where: u, v are a pair of vectors of translation and d(x) is the pixel depth, i.e. the distance from Kinect to the point projected on x.

This is a very simple feature. In fact it is just a difference in the depths of two pixels that are misplaced to u and v. (By varying u and v, we obtain a set of features). The only complication lies in the fact that the offset is standardized by the source pixel depth, i. e. it is divided by d(x). This makes the offset independent of the depth and correlates them with the visible body sizes.

These features measure something associated with the three-dimensional shape of the region around the pixel; but another issue is what if they are enough to distinguish the leg from the hand.

The next stage accomplished by demand is the training of the classifier's variety called the "Random forest", which is the set of decision trees. Each tree was trained on a set of features on depth images that before were attached to the proper body parts. I. e. the trees were rebuilt as long as they did not give correct classification for a particular body part on a test pattern of images. The training of three trees per 1 million images on a 1000-core cluster took about a day.

The trained classifiers give the probability of belonging of a pixel to a particular body part; and the next stage of the algorithm simply selects the region with maximum probability for parts of each type. For example, the area shall be assigned to the category "leg" if the "leg" classifier gave maximum probability in this area. The final stage is calculating the assumed location of the joints relatively to the areas identified as specific body parts.

It is quite simple to calculate all of this having the depth values of at least three pixels; then one can use GPU. Therefore, the system can process 200 frames per second and does not require the initial standard position. Since each frame is analyzed independently, and there is no tracking as such, then there is no problem with loss of the body image; it is possible to process some of the body images at a time.[29]

Kinect is a significant achievement. It is based on standard pattern identification. It is also necessary to take into account the availability of large multi-core computation power, which allows making the training set enough large. Spending a lot of time on the training is one of the peculiarities of the identification's methods, but then the classification itself can be accomplished very quickly.

Data streams

The Kinect system has three data streams at the output: Color Stream, Audio Stream and Depth Stream. SDK is built on these streams.
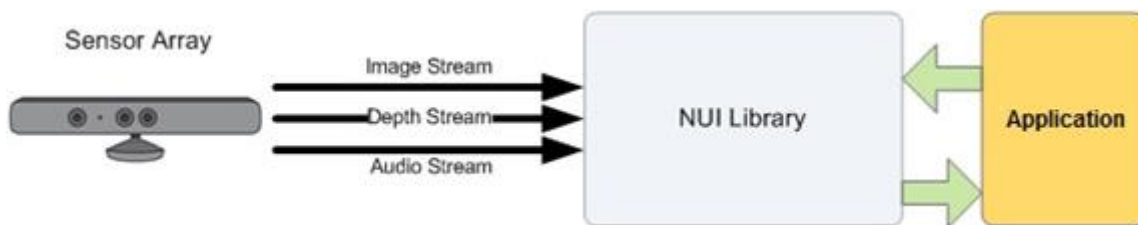
Fig. 2.6. Data streams

Having aimed to use the capabilities of Kinect, the first thing one need to do is to select the necessary sensor and initialize the essential data streams.

After that, it is possible to set and turn on the necessary streams for the selected sensor.

The video stream from the sensor

The developer is free to set the quality level and image format initializing video stream. The amount and speed of the transmitted data from the sensor directly depends on the quality level. They are limited by the carrying capacity of USB 2.0. So for an image of resolution 1280x960

the quantity of frames is 12 frames per second, and for images of resolution 640x480 it is 30 frames per second. The image format is determined by the color model and can be either RGB or YUV.

Combinations of quality level and images format are represented by the enumeration *ColorImageFormat*.

Three of its values define 32-bit encoding of each image pixel:
RgbResolution1280x960Fps12, RgbResolution640x480Fps30 and
 YuvResolution640x480Fps15. The fourth one is 16-bit RawYuvResolution640x480Fps15.
[29]

The audio stream from the sensor

Kinect has a built-in set of four microphones that use a 24-bit analog-to-digital converter, and the built-in evaluator of acoustical signals includes echo cancellation and noise reduction. Each microphone is mounted in such a way that it has small directional property. It depends on the developers if to use the echo cancellation or noise reduction, i.e. these options are set during the initialization of the audio stream. The optimal distance between the speaker and the sensor is about 1-3 meters.

The audio capabilities of Kinect can be used in many different ways, for example, for high-quality capture of the audio signals, determination of the position of the audio signals or speech recognition. [29]

The data stream of the rangefinder from the sensor

This stream is formed from the frames in which each pixel contains the distance (in millimeters) from the plane of the sensor to the nearest object in the specific coordinates of the field of viewing of the camera. As in the case of the video stream, for the data stream of a rangefinder it is possible to set the resolution of a single frame, which is determined by the enumeration *DepthImageFormat*.

At frequency 30 frames per second, the developer is free to choose the resolution 80x60 (Resolution80x60Fps30), 320x240 (Resolution320x240Fps30) and 640x480 (Resolution640x480Fps30).

The distance value at each pixel is encoded by only 13 bits, and 3 bits are intended to identify a person. If the distance to the object appears to be behind the working range, in the 13 bits there will return zero or constant. If at initialization of the sensor one provides the possibility for the tracking of human figures, in the 3 bits there will return a sequence number (1 or 2) of the detected human (if at this point the human has been found, otherwise there will return zero). [29]

Tracking of human body

With the help of this function, Kinect can recognize the human body and his movements. Kinect can determine that within sight of the sensor there can be as many as six people, but the detailed information can be gathered only for two of them. It is presented on the figure 2.7.
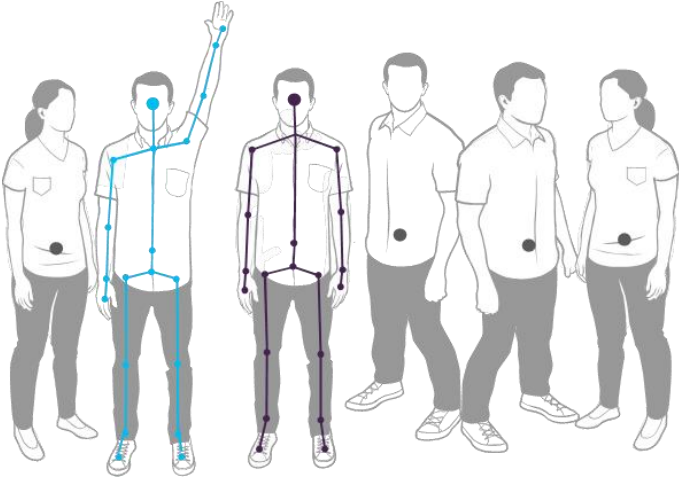
Fig. 2.7. The human body's recognition

The sensor by default: the detailed skeleton is built only for two of the recognized bodies. The rest of them are just determined. The points of the built skeleton are called Joints. The *Joint Type's* enumeration values are shown on the picture of Vitruvian man.
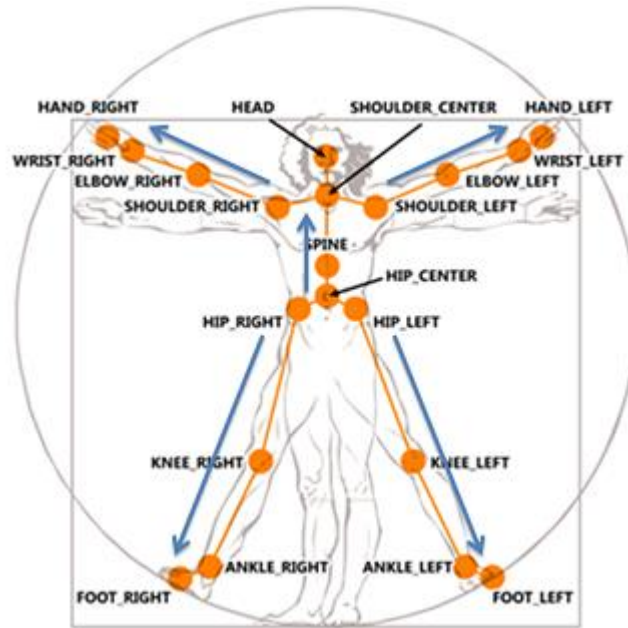
Fig. 2.8. Vitruvian man

The 20-nodal skeleton was mentioned earlier. It is not always possible to build it. That was how the mode called the seated skeletal tracking came to be invented. In this mode, the sensor builds an incomplete 10-nodal skeleton. [31]
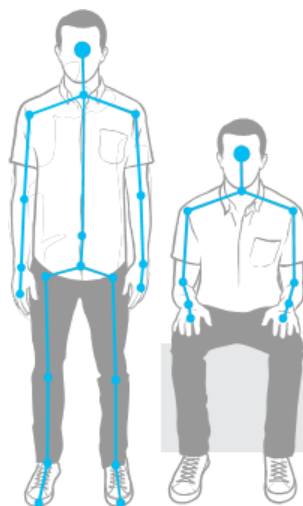
Fig. 2.9. Seated skeletal tracking

For recognition of the Kinect figures it is enough to set the *TrackingMode* property of the *SkeletonStream* object during the initialization of streams. In the seated skeletal tracking mode the sensor can recognize up to six figures and keep tracking two figures. But there are also some peculiarities. For example, if it is necessary the sensor to "notice" somebody, they need to move

or wave in front of the sensor, while in the recognition of the complete skeleton mode it is enough to stand in front of the sensor. [29]

2.3.2. Kinect Studio
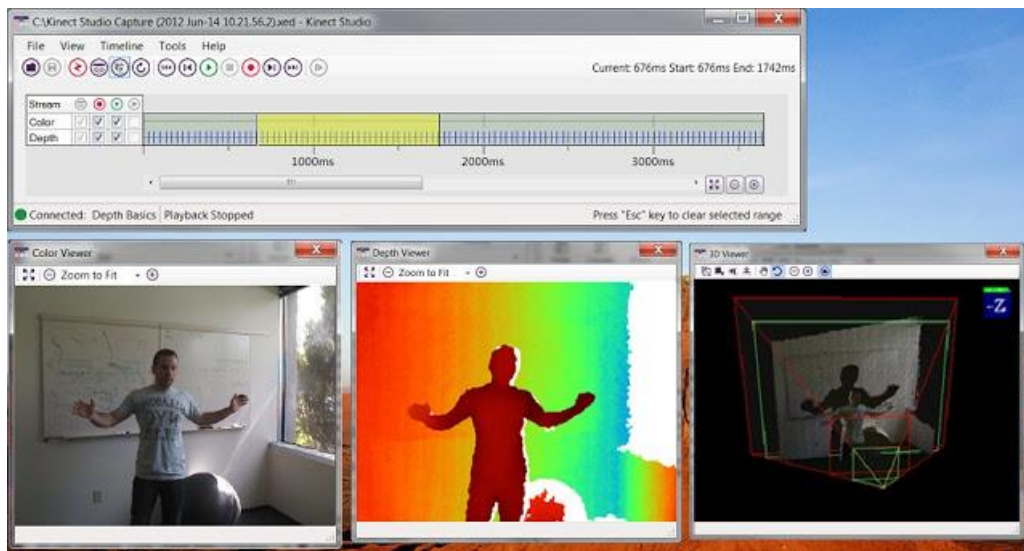
Fig, 2.10. Kinect Studio's operation

Kinect Studio can be seen as a debugger or emulator. Its function is very simple: to help one record the data coming from the sensor and send them to your app.

To start working with Kinect Studio, it is necessary to connect to the application and choose the sensor. Now everything is ready to start recording the data of the sensor or injection of the saved data. [29]
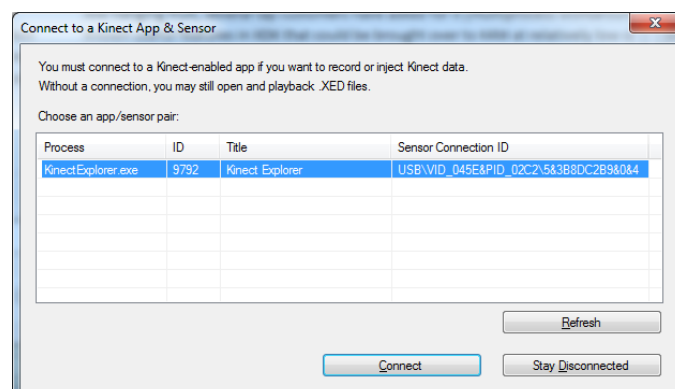
Fig. 2.11. The selection of the sensor

2.4. OpenSim

OpenSim is software pack which you can use to build, modify, and analyze the musculoskeletal model and to simulate dynamic motion. The program supports the API interface. With the appearance of the release, thousands of people began to use it in different fields: biomechanical study; projecting of medical, orthopedic and rehabilitation equipment; sports industry; computer animation and for studying at universities. The program creates the platform which can be used by the developers to build one's own library of elements, modify them and carry out all sorts of tests.

The OpenSim core is written in the high-level language C++ and the GUI is written in Java. The opportunities of the program allow projecting parts for each specific case, calculating the collision and their interaction.

The program's opportunities:
• creating animations and exporting movements in the film;
• constructing the graphs on the basis of the analysis results;
• the possibility to scale the model;
• computing angles between the model elements by the means of the markers;
• creating simulations of compound movements;
• analysis of the simulation.

The software OpenSim is the available surroundings of modeling created for a better integration of dynamic models in the field of science about the movements and for separation of the modeling technologies and modeling itself. The advantages of OpenSim are that it is widely used for the musculoskeletal modeling (i.e. it is supported by kinematic and dynamic analysis of the system and the estimation of muscular efforts); it is continually evolving and is the software of free access.

Therefore, it is easier to exchange models than when using commercial software, which is not publicly available. When loading musculoskeletal model in OpenSim, there are several analysis tools. First of all, it becomes possible to zoom using the "Zoom tool". Then using the "Tool for inverse kinematic analysis" the movement, recorded during the experiment, is associated with the model; the kinematics is determined in generalized coordinates. Next using the "Tool for

inverse dynamic analysis" there are calculated the closing force and rotational moments in the joints of the model on the basis of defined motion, geometry, external loading, and mass and inertial properties of the model. And finally, there are computed the muscle activation/forces with the use of the approach based on static optimization.

OpenSim is integrated with *Simulink* due to the S mechanism or the function of MATLAB. Their interaction demonstrates the system's operation as with feedback as without it. At a time when the control system without feedback is used in *MATLAB/Simulink*, the *OpenSim Forward Dynamics Tool* is reproduced individually. The control system with feedback adds the unique possibility to control feedback to OpenSim, which is necessary to model most human movements.

There is a number of programs which allows carrying out the modeling of muscle work during accomplishment of various human movements.

It lets users develop the models of musculoskeletal system, to track the muscle length, to determine the rate of muscle actions, the shoulders, the moment of force, and some other features during movements.

The program window of OpenSim in the modeling of muscle activity of the lower limbs; musculoskeletal and dynamic modelings have emerged as powerful tools to study the biomechanical causes of deviations in movements and projection of various options for treating of muscular pathologies. The users of OpenSim have the opportunity to consider fundamental questions of mechanics, the most significant fields of rehabilitation medicine, including strokes, spinal cord trauma and prosthesis. [2]

The OpenSim program is offered for studying and identifying the problems of human gait.

2.5. Experimental studies

2.5.1. Analysis problems

For further checking of the developed system it is necessary to conduct a range of experiments. The subjects must differ in growth, age and sex.

2.5.2. Test persons

The test persons were men and women of different ages and with different types of gait. They also differed in physiological parameters such as height and weight. After conducting all the experiments we have 8 data sets of different people.

2.5.3. Researches with the use of the Vicon system

2.5.3.1. Research methodology of Vicon

The experiment is conducted at the research centre of St. Petersburg State University of Film and Television on the marker optical passive motion capture system *Vicon*. The area for capture is less than 3×3 m^2. The test person puts on the suit with 53 markers which define each bone of the test person.

2.5.3.2. Vicon's experimental procedure

In the experiment there were involved men and women of different ages and builds. Firstly, the cameras are calibrated. The camera's calibration is a special procedure aimed at the determination of the relative position of the cameras. During the camera calibration, the system writes a special clip, which consists of movements made by a calibrator with known location of the markers. After the recording there occurs the system's calibration on the basis of the recorded clip, in which the system determines the exact coordinates of the cameras relative to each other. The structural chart of the calibration process of the mocap system is shown on the figure 2.12.
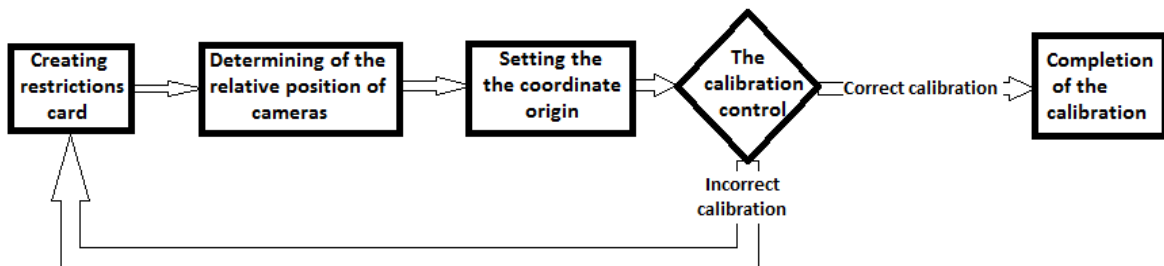
Fig. 2.12. The calibration process of the mocap-system

After the calibration process, the mocap system can capture the coordinates of the markers. However, during the movement the markers on the body of the test person inevitably disappear from the field of vision of the cameras. There are several algorithms to reconstruct trajectories of the markers missing from the field of vision of the cameras. One of them is a solid-state reconstruction. The algorithm consists of selecting a group of markers (4 or more) on a rough body part (without joints), the subsequent determination of the position of this body part on the 3 markers and the recreation of one or more missing markers. For this algorithm to operate the automatic recognition of the names of the markers determining their position on the body of the test person is required. The calibration of the character is required for automatic determination of the names of the markers. The character is the Blade object containing a skeleton, reduced the size for the specific location of markers on the test person (the creation of a new character is required after changing dress of the test person or changing the position of a single marker). The character calibration is the process of fitting a standard skeleton to the sizes and proportions of the test person. For calibration of the character Blade uses the special calibration clip in which the test person produces movements by all the body parts. Using the data character, Blade produces the automatic recognition of the names of the markers at any position of the subject. The skeleton and the markers with the automatically recognized names are used for later use of mocap data in third-party applications. The structural chart of the process of the test person's preparation is shown on the figure 2.13.
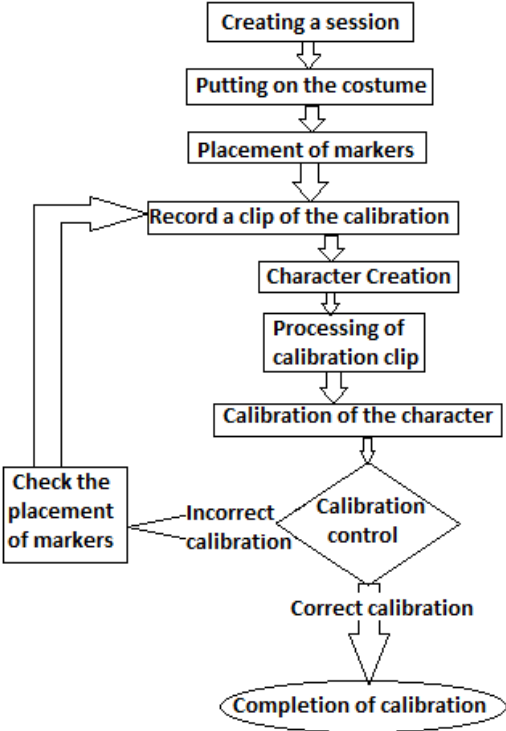
Fig. 2.13. The process of the test person's preparation

The suit has to be fitted on the figure of the test person with the use of stickum (or Velcro) included into the suit set. Long hair must be tucked under a hat. There should not be pleats or other elements that may block the visibility of the markers.

There are placed 53 markers on the test person's body. 5 of them are placed on the head, 14 on the trunk, 16 on the arms, and 18 on the legs.

2.5.3.3. The placement of the markers on the feet

There are placed 18 markers on the legs (fig. 2.14, 2.15), 10 of them on the feet (fig. 2.16). Each 2 markers are fixed at the points of input and output of the spin axis of the left (LKNE, LKNI) and right (RKNE, RKNI) knees. For improving the visibility of the markers it is allowed to displace the markers LKNI and RKNI forward by 1-2 cm. Then additional markers are placed on the hips (LHIP and RHIP) and the shins (LSHN, RSHN). Avoid symmetrical placement of the additional markers relative to the knees' markers.
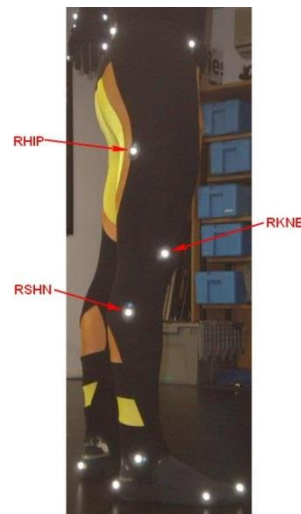
Fig. 2.14. The markers of the right leg.

Fig. 2.15. The markers of the right leg
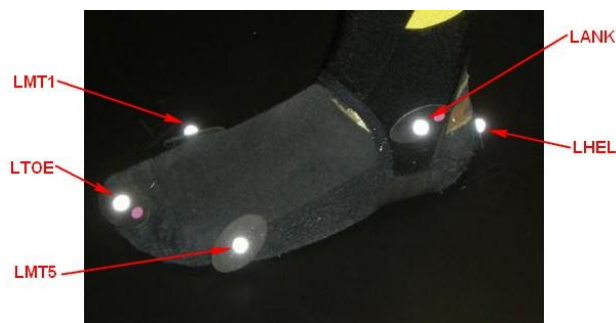
Fig. 2.16. The markers of the left foot with the notations

The markers have the following markings:

• LHIP (Left HIP) - left hip;

• LKNE (Left KNEe) - left knee;

• LKNI Left Inner KNee) – left inner knee;

• LSHN Left SHIN (lower leg) – left shin;

• RHIP (Right HIP) - right hip;

• RKNE (Right KNEe) – right knee;

• RKNI (Right Inner KNee) – right inner knee;

• RSHN (Right SHiN (lower leg)) – right shin;

• LANK (Left ANKle) - left ankle;

• LHEL (Left HEeL) - left on the heel;

• LMT5 Left 5th MetaTarsal (outside of the foot) - left at the beginning of the little toe;

• LMT1 (Left 1st MetaTarsal (inside of foot)) - left at the beginning of the big toe;

• LTOE (Left TOE (front of the foot)) – left toe;

• RANK (Right ANKle) – right on the ankle;

• RHEL (Right HEeL) - right on the heel;

• RMT5 (Right 5th MetaTarsal (outside of the foot) – right at the beginning of the little toe;

• RMT1 (Right 1st MetaTarsal (inside of foot) – right at the beginning of the big toe;

• RTOE (Right TOE (front of the foot)) - right toe.

Then the program creates a new skeleton which will have the characteristics of the test person after the calibration.
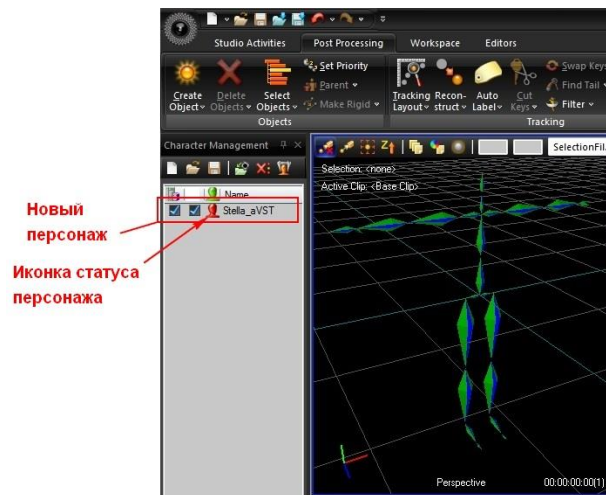
Fig. 2.17. Ungraduated skeleton of the new character

During the recording of the calibration clip, the test person makes special motions to record the maximum of possible body's movements. The structural chart of post processing is shown on the figure 2.18.
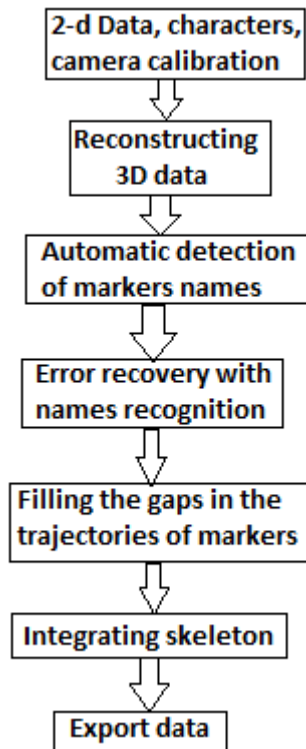
Fig. 2.18. Structural chart of post processing

After that, it is possible to do the necessary capture.

2.5.3.4. The procedure of capturing

Walking in a circle

1. The test person stands in T-position for 3-5 seconds

2. The test person makes 3 steps forward to the edge of the field

3. The test person begins to walk in a circle

4. The test person breaks into a run at the third circle

5. The test person makes 3 steps to the center of the field

6. The test person stands in a T-position for 3-5 seconds

Walking on the treadmill

1. The test person stands in T-position for 3-5 seconds

2. The test person begins to walk on the treadmill

3. The test person breaks into a run

4. The test person stands in T-position for 3-5 seconds

All the research along with the setting and switching of the devices takes about 25-35 minutes.

Then there is cleaning of the results of motion capture in order to recover the lost markers. Then, the obtained data is exported in a data format which can be opened with the help of the popularized software packs.

2.5.3.5. Processing of the obtained data

2.5.3.5.1. Basic data

The data of each research is recorded in real-time by the Vicon Blade software. The file consists of a heading and the data itself. The data is written to the file by the movement of each limb; each movement can be viewed. Then, when the capture ends, the lost markers are restored. The cause of the markers' lost is overlapping of them or the system mixing up of the markers. Sometimes there appear new markers due to the glares of long loss of a marker.
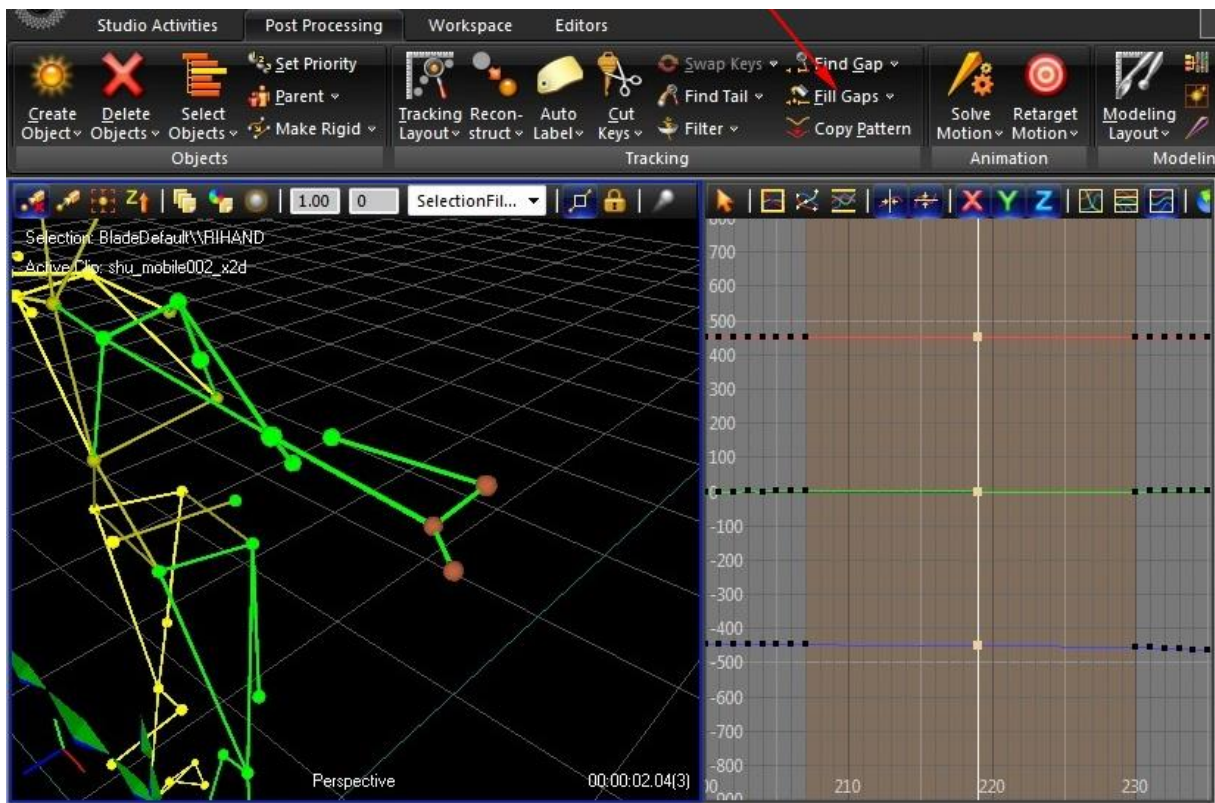
Fig. 2.19. The image of the lost marker

The data comes in different formats and each format shows the tasks of the skeleton and its movement in different ways.

Examples of the formats are:

Normally Blade records in the format .HDF. The format can be opened only by Blade, so this format is not suitable. In process there used the data stored in other formats.

In the BVH format there is the task of the test person's skeleton, there are given the values of the bones' length and their position.

Fig. 2.20. The example of the data in the BVH-file

2.5.4. The research with the help of Kinect for Xbox 360

2.5.4.1 The research method of Xbox 360 Kinect

The research of the Kinect system occurs simultaneously with the research of the Vicon system, so the test person walks about the field with the size of less than 3×3 m^2.

2.5.4.2. The procedure of the Kinect Xbox 360 experiment

The experiment involved men and women of different ages and physique. The motion capture occurs using the software pack of iPi Recorder 3. It is necessary to install the Microsoft Kinect SDK, OpenNI, PrimeSense Sensor drivers for its work, then to connect up Kinect Xbox 360.
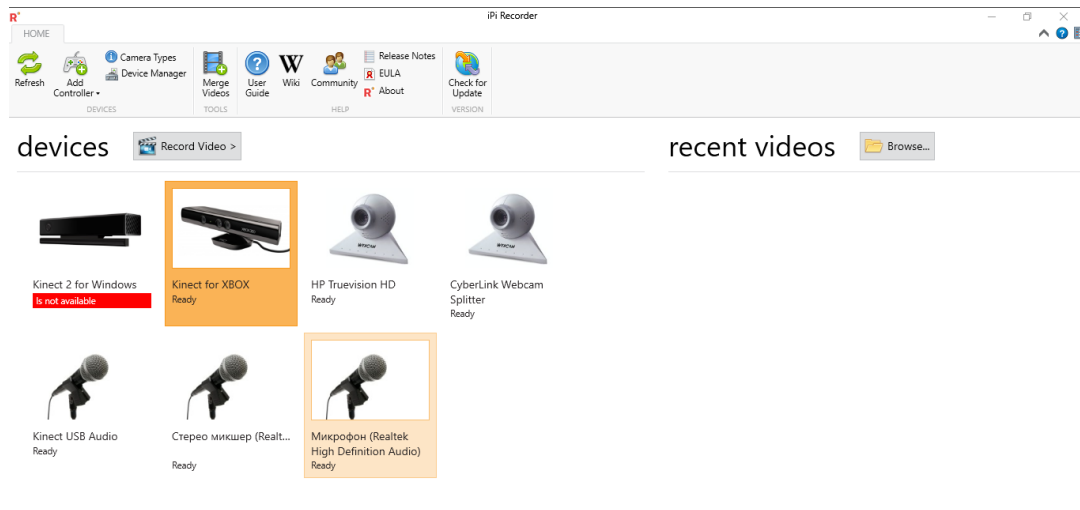

Fig. 2.21.

Firstly, there occurs the calibration of the cameras. During the calibration there shouldn't be people in the frame. It is necessary for identifying people and building skeletons for them while shooting in the frame.
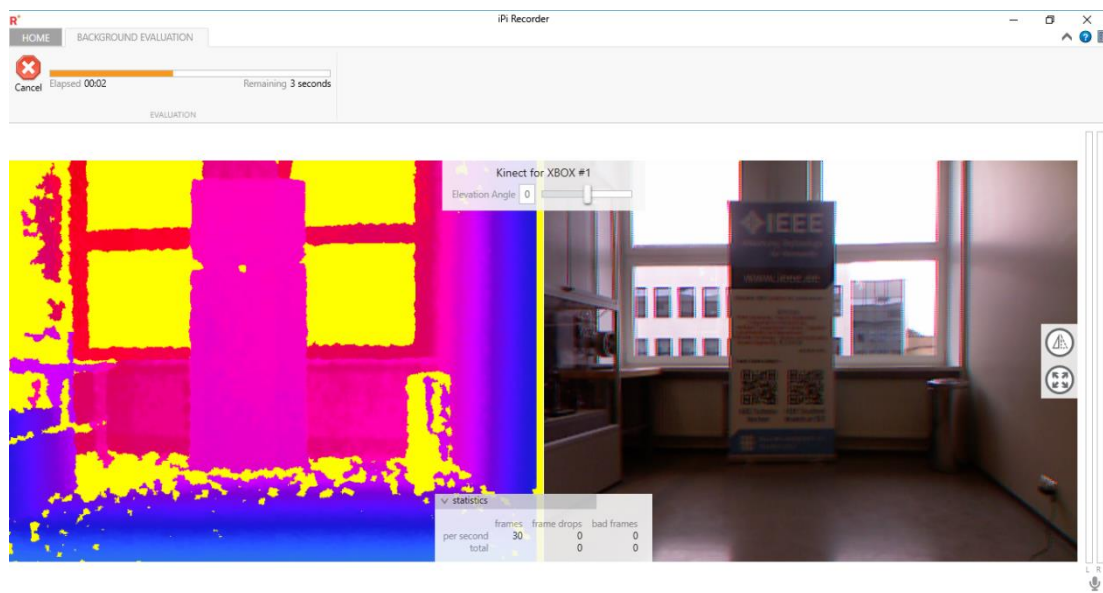

Fig. 2.22. The calibration of the cameras

Then there is the recording of the human movements.

Walking in a circle

1. The test person stands in T-position for 3-5 seconds

2. The test person makes 3 steps forward to the edge of the field

3. The test person begins to walk in a circle

4. The test person breaks into a run at the third circle

5. The test person makes 3 steps to the center of the field

6. The test person stands in a T-position for 3-5 seconds

Walking on the treadmill

1. The test person stands in T-position for 3-5 seconds

2. The test person begins to walk on the treadmill

3. The test person breaks into a run

4. The test person stands in T-position for 3-5 seconds
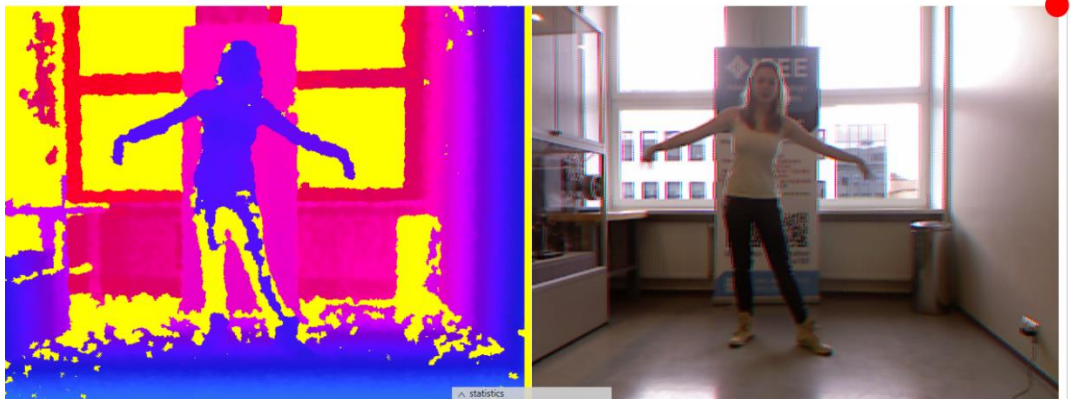
Fig. 2.23. The motion recording

Then, using the software pack *Brekel Kinect Pro PointCloud* there is constructed the skeleton for the point clouds.

2.6. Creating of a model in the software pack OpenSim

As a result of the obtained data from Vicon and Kinect, we have the simultaneously obtained sets of indicators about the person's movement in each system. In the research there took part men and women, which differ in size, weight, and age.

For creating of models, presented further, we will use the data on a man of 23 years, with the weight of 77,8 kg, and the height of 184 cm. As we create the model only of the lower limbs, we will also take into account the length and weight of the object's limbs:

Table 2.1. Model parameters

Limb	Length, m	Mass, kg
Foot	0,26	1,5
Cnemis	0,45	4,5
Hip	0,5	11
Pelvis	0,2	-

Limbs' length and growth were measured with the help of a tape measure, the object's weight was measured by scales, and limbs' masses – by means of a mass calculator for amputations, and therefore we do not indicate the pelvis mass, because in the work there is no need of these data.

As a result, we have the data about the object and the data obtained by motion capture systems Vicon and Kinect in the BVH format. Next, we will consider the data of the Vicon motion capture, and on the basis we will make the algorithm for creating the model in the software pack OpenSim.

2.6.1. Data select

We carried out the motion capture of an object in a circle at the field of $3*3$ m^2 and movements on a treadmill. For the model we will use the data obtained during the movements in a circle. While moving in a circle, the object first stands in the T-position; then takes a step forward and begins to move clockwise. Initially, the object just walks around, and then breaks into a run.

Vicon.webm

Video 2.1. The object of the T-position walks in a circle (the video is provided on the disk)

In the video 1 it is noticeable how the object of the T-positions walks in a circle. Using this movement, we will create a model of the lower limbs' motions. To create the model we need the data in the format .trc. This format provides information on the number of markers and the motions.

Using the data presented on video 2.1, we create 2 files (the files is provided on the disk). The first file is a set of markers in the process of the object calibration when it is in the T-position.
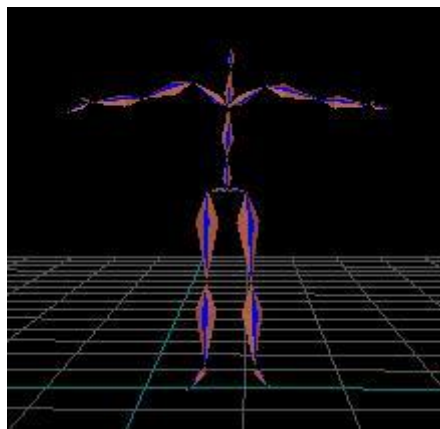
Fig. 2.25. The object in the T-position

As a result we get a file in the format .trc, which represents the number of markers and information about the object.

Next, we select the period of the step according to which the model will be created. In this paper we use the step that is made when the object has already walked a couple of steps, because this step is easier to analyze in both systems. The period of this step is shown in the video 2.2.

Vicon data model.webm

Video 2.2. The period of a step (the video is provided on the disk)

Similarly, there occurs the selection of the data obtained with the help of Kinect. The data, received by the systems Vicon и Kinect, were received at the same time; relatively, they coincide in the movements and time of the movements.

2.6.2. The creating of a model in OpenSim

OpenSim is a software pack which one can use to build, modify, and analyze the muscular-skeletal model and to simulate the dynamic movement. OpenSim is a software open source pack that allows us to create models according to available data.
To create a model, we use the file of the standard lower limbs' movements, which has the data on the movements of a particular object and by what means this object operates upon the platform. We used the standard file of the gait *Gait2392_Simbody* (the file is provided on the disk) with the data on a normal gait (the files is provided on the disk).

Using this file we personalize and create a model with the help of the data on the object, the T-position and the object's motions.
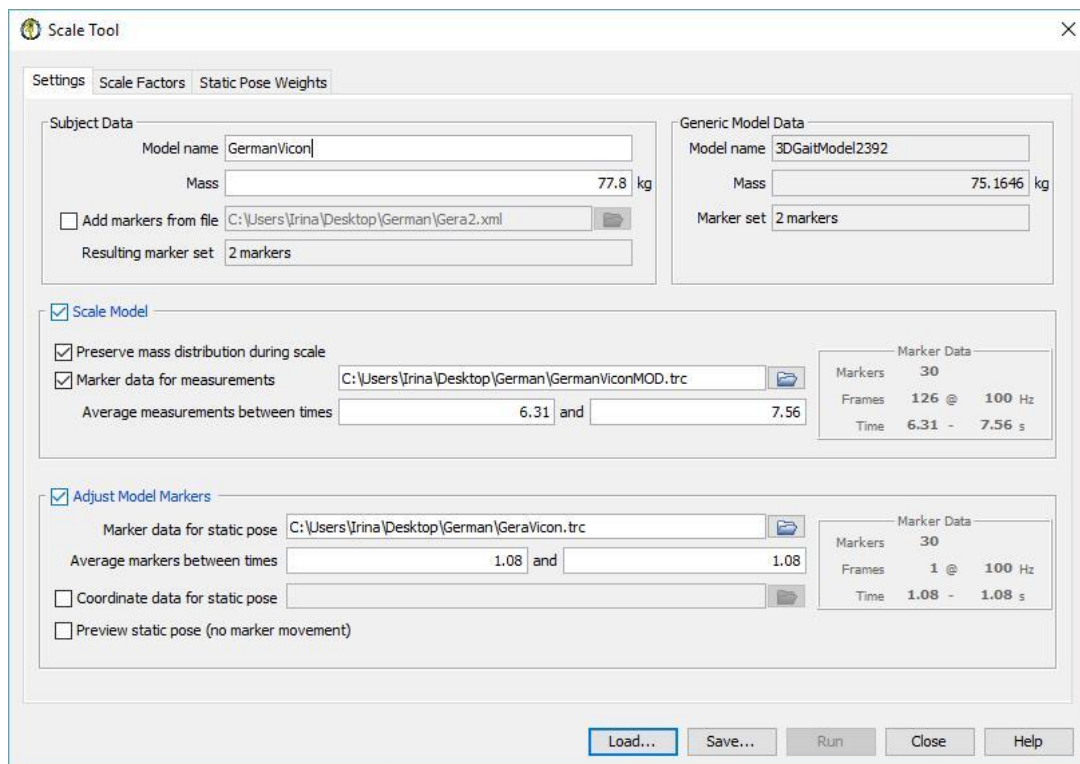
Fig. 2.26. Creating of a model

Then the file of the model is calibrated according to the data we entered. As a result, we have a file that will be used by our created personalized model (the file is provided on the disk).
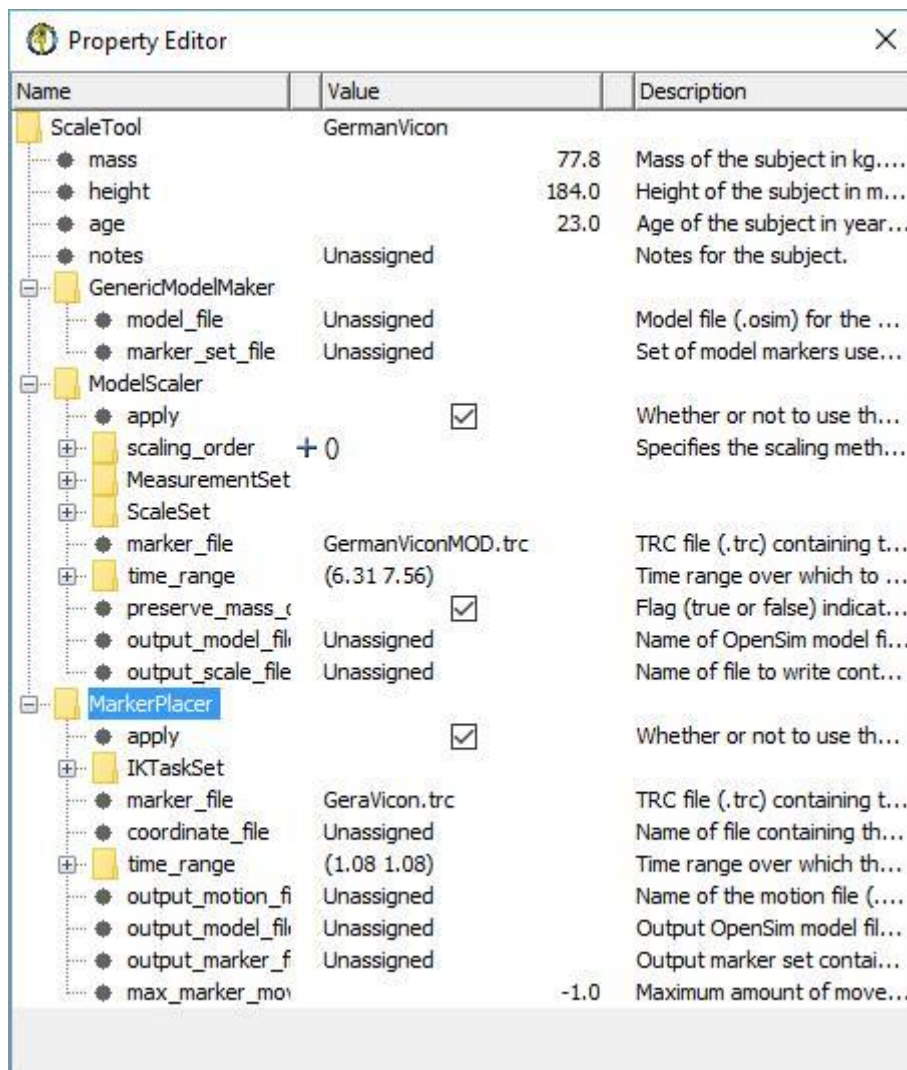
Fig. 2.27. The result of the model creating

As a result of the work, we obtain the file the object's gait created according to the characteristics of the object. This gait is presented in the video 2.3.

Model.webm

Video 2.3. The gait by taking into account the features of the object (the video is provided on the disk)

For the model of the data, obtained with the help of Kinect, we carry out the analogous algorithm (the files is provided on the disk).

3. THE ANALYSIS OF VICON AND KINECT MODELS

In this work, the motion capture was made by two motion capture systems - Vicon and Kinect.

The Vicon system consists of 10 optical cameras, infrared emitters and bonding servers. The object puts on a fitted suit made of Velcro which the reflecting markers are attached to. The emitters project the infrared rays in the capture area; the cameras receive the reflected rays from the markers and determine the position of the markers in space.[4] This system is stationary; it hampers that the object puts on the suit with the markers. The cost of the system Vicon is $12 500.

Another system that I used is the markerless motion capture system Kinect. Kinect is a device of small size, consisting of an IR projector emitting infrared radiation, an infrared receiver, a conventional optical camera and a chip, developed by company Primesence, which allows one to recognize the movements of objects and people in three-dimensional space. The device projects infrared rays and receives them back, analyzing the time spent on the path of the ray, and thus, building a depth manuscript of the images. For the capture of a body it is necessary to observe the minimum conditions: fitted lackluster clothing, a sufficient distance from the sensor and absence of the object during the calibration. Further Kinect detects the object according to the data from the sensor and builds in software the skeleton for the object. The Kinect system is a mobile system; to use it one need the system itself and a computer. The cost of the system Kinect is $100-$250, which is significantly cheaper than the Vicon system. [28]

Next, we consider the data obtained by the systems we selected; in the videos 3.1 and 3.2 there are reproduced the models of the object's motions according to the data obtained using the motion capture systems Vicon and Kinect.

Vicon.webm

Video 3.1. The data obtained with the help of the motion capture systems Vicon (the video is provided on the disk)

Kinect.webm

Video 3.2. The data obtained with the help of the motion capture system Kinect (the video is provided on the disk)

As a result of the visual motion study, we can notice that the system Kinect builds the skeleton of the upper limbs with a significant error (the figure 3.1.), so it is not suitable for working with the upper limbs.
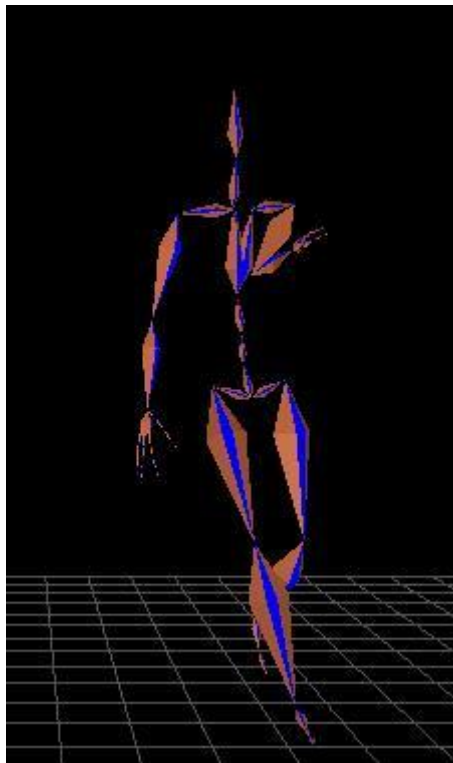
Fig. 3.1

Therefore, we will analyze the accuracy of the lower limbs' motions data to determine the possibilities of using these motion capture systems for motion study of the lower limbs and the possibility of changing the expensive Vicon system with the Kinect system.

3.1. The analysis of models in OpenSim

The software OpenSim is an open source simulation environment of dynamic models. When loading the musculoskeletal model in OpenSim, there are available several analysis tools. First of all, it becomes possible to zoom using the "Zoom Tool". Then using the "Tool for

reverse kinematic analysis" the movement recorded during the experiment is connected with the model and the kinematics in generalized coordinates is determined. Next, using the "Tool for inverse dynamic analysis" the resulting forces and rotational moments in the joints of the model on the basis of the defined motion, geometry, external loading, mass and inertial properties of the models are calculated. And finally, computed the muscle activation/forces are computed with the help of the approach based on static optimization. [2]

For the analysis of the models in OpenSim, we use files with the file extension .sto. The file extension .sto is connected with the file type "OpenSim Storage" (OpenSim Storage .sto). Open source simulation aids of the movements and physical interaction of people, animals and OpenSim robots uses the .sto files to store the data on the movements in relation to the timebase in a special dual format (the header section and data section), similarly to the motion data file (.mot), which are also used in OpenSim. [34]

As the files .sto, as well as the files .mot are loaded to the model and there is possible only the visual analysis, we will use Plotter appropriate for OpenSim to compare the standard model of gait available among the standard models and the models obtained with the use of the data from the motion capture systems.

Below there are charts obtained according to the data on the models. The data of the standard model OpenSim, which contains the data on the object, are denoted with claret red colour; the data obtained from the model, created with the help of the Kinect system, are denoted with deep blue colour; the data obtained with the help of the Vicon system are denoted with green colour.

Chart 3.1. Right knee

As you can see in the chart 3.1, the general dynamic motion, obtained with the help of simulation of the data in OpenSim, which were received with the use of the motion capture systems, and the data, which were received from the model, are close to each other. The data obtained using the Vicon system repeat the chart of the right knee's motions more precisely than the data obtained with the use of the Kinect system, but the angle change of the knee in the Kinect system is more precisely. This may be due to the approximation of the lower limbs' movements in the process of the motion capture by the systems Vicon and Kinect. The discrepancy between the data over time may be due to the data lagging.
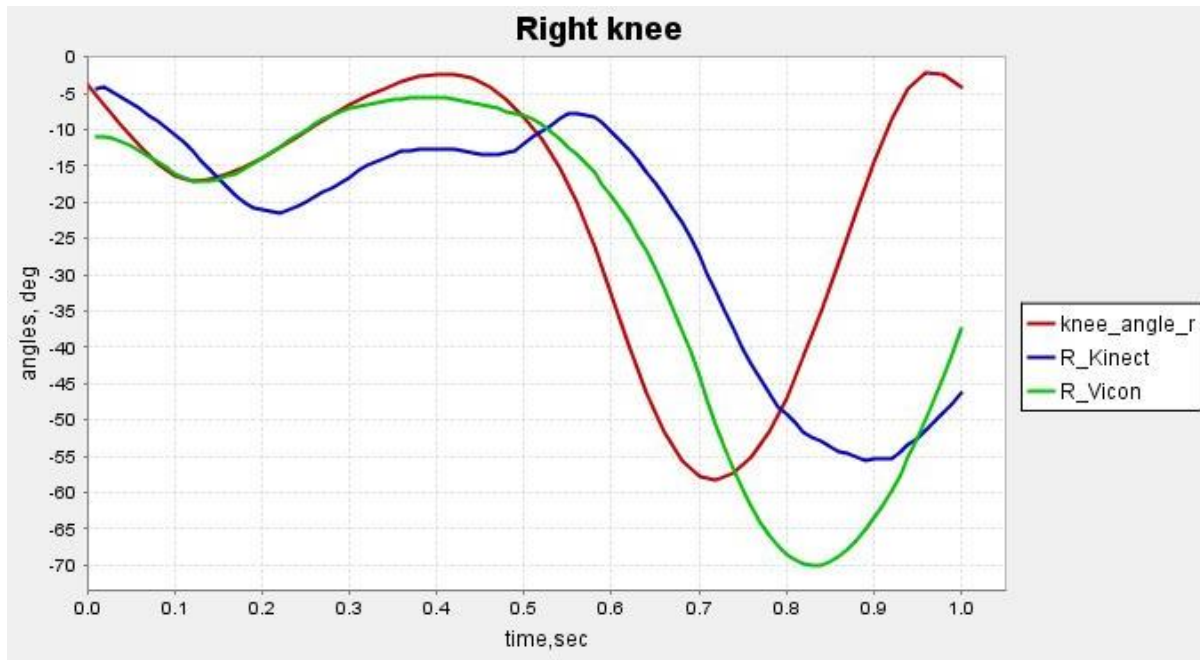
Chart 3.2. Left knee

As you can see in the chart 3.2, the general dynamic motion, obtained with the help of simulation of the data in OpenSim, which were received with the use of the motion capture systems, and the data, which were received from the model, are close to each other. The data obtained using the Vicon system repeat the chart of the left knee's motions more precisely than the data obtained with the use of the Kinect system, but the angle change of the knee in the Kinect system is more precisely. This may be due to the approximation of the lower limbs' movements in the process of the motion capture by the systems Vicon and Kinect. The discrepancy between the data over time may be due to the data lagging.
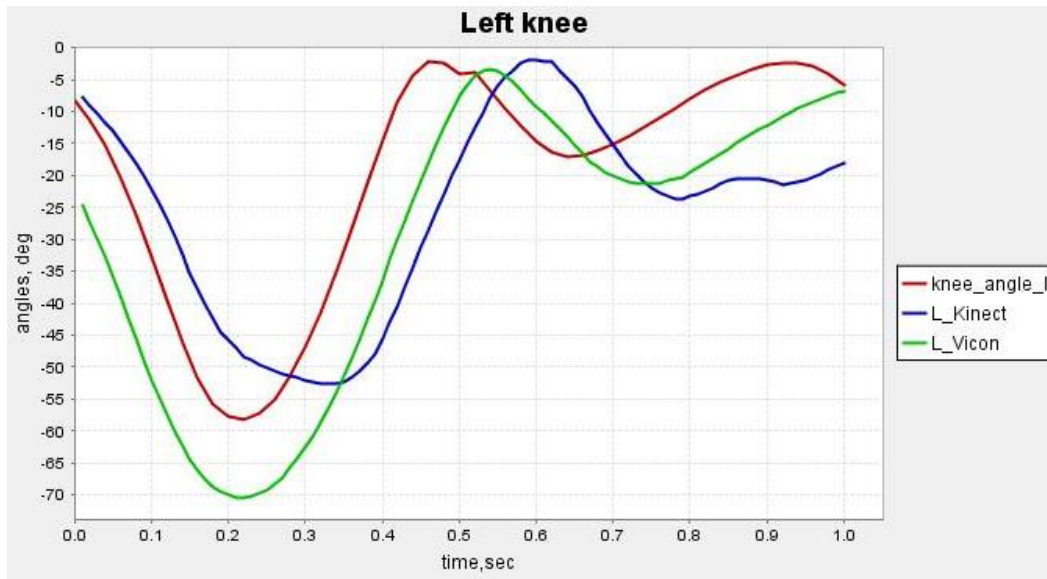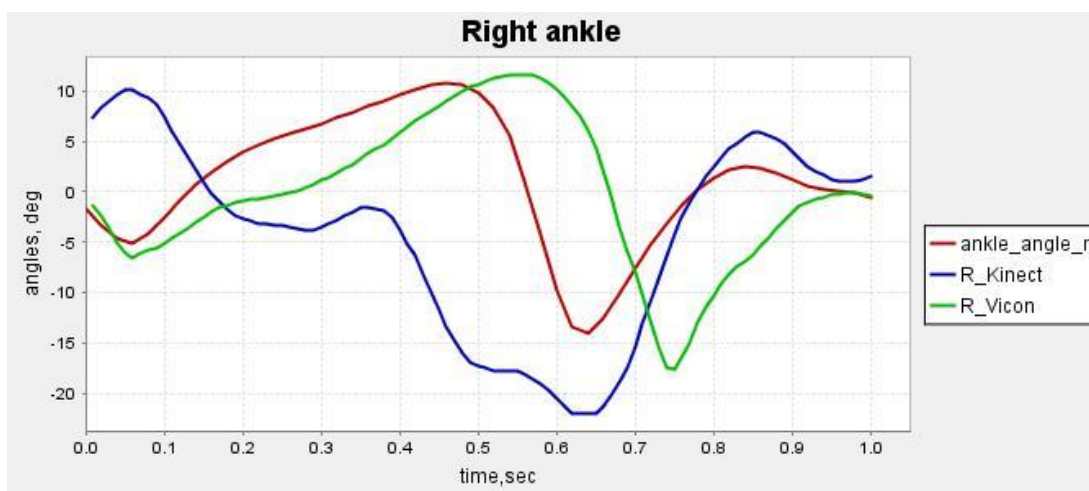

Chart 3.3. Right ankle

As you can see from the chart 3.3 the general dynamic motion obtained with the help of simulation of the data in OpenSim, which were received using the motion capture systems, and the data, which were received from the model, have common stress periods. The data obtained using the Vicon system repeat the chart of the right ankle's motions more precisely than the data obtained with the use of Kinect, because Vicon computes the angle changes by approximating the available data on the markers, while the Kinect system builds the skeleton defining the object in space and can make mistakes when constructing more accurate data, what we see in the chart 3.3. The chart received with the help of Kinect, is close to the stress periods, but the angles differ from the angles obtained using the Vicon system and OpenSim models. The discrepancy between the data over time may be due to data lagging.
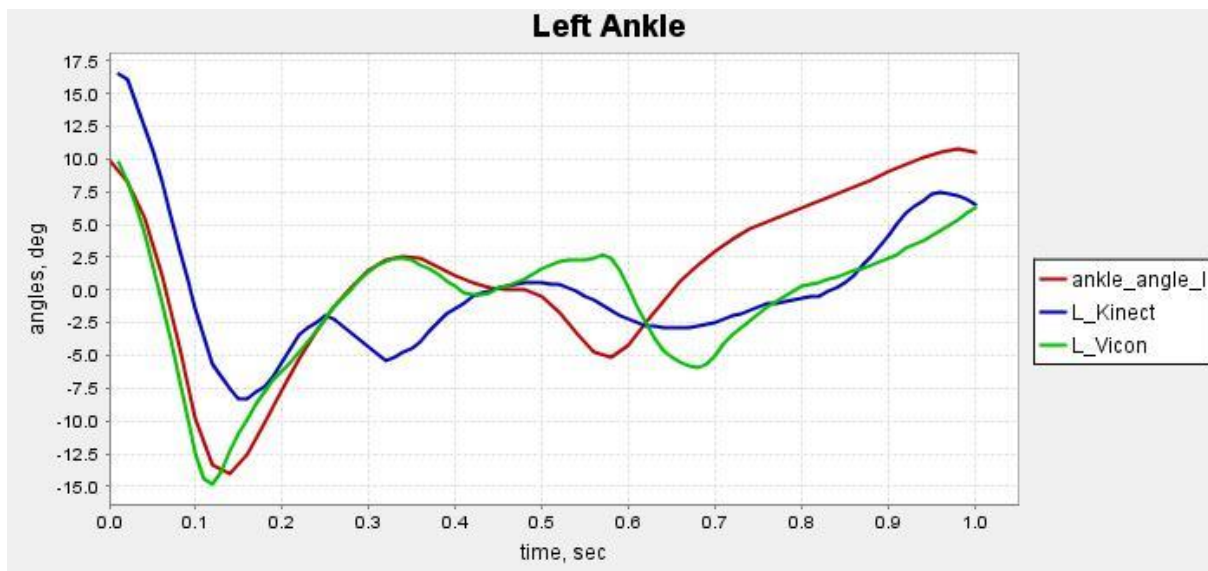
Chart 3.4. Left ankle

As you can see in the chart 3.4, the general dynamic motion obtained with the help of simulation of the data in OpenSim, which were received using the motion capture systems, and the data, which were received from the model, are close to each other. The data obtained using the Vicon system repeat the chart of the left ankle's motions more precisely than the data obtained using Kinect, because Vicon computes the angles change by approximating the available data on the markers, while the Kinect system builds the skeleton defining the object in space and can make mistakes when constructing more accurate data, what we see in the chart 3.4. The chart obtained with the help of Kinect is close to the stress periods, but has large angle spread with t=0.25 sec.; the chart obtained with the use of the data from the Vicon

system begins to differ from the OpenSim model with t=0.45 sec. The discrepancy between the data over time may be due to the data lagging.

As a result of the analysis we see that the Vicon data are more accurate to build models, as well as the charts obtained from the model built using the Kinect data, although they contain errors, they give us the vision of the model's motion and the possibility to analyze it.

3.2. Analysis of the models in MatLab

Let's compare the automation tools of mathematical calculations. In this type of software, there are many analogies of various directivities and principles of construction. Mathcad is often compared with the software packages such as Maple, Mathematica, MATLAB, as well as with their analogues MuPAD, Scilab, Maxima, etc. However, an objective comparison is complicated due to the different purposes of their use.

The MATLAB system is both the operation environment and programming language. The user can write specialized functions and programs that are designed in the form of M-files. Classifying by task type, one can form them in the application software packages (ASP). MATLAB (Matrix Laboratory) is designed primarily for working with arrays, almost all the algorithms of computation are optimized to work with vectors. The abundance of tools for working encourages presenting as much initial data in the form of matrices as possible. Instead of the elementary functions, MATLAB includes a number of special mathematical functions. Such functions are solutions of some differential equations or notations of integrals of a certain type.

Arguments of special mathematical functions can be as separate numbers, as number groups. If the argument of a special function is an array, as a result we'll get the array of the same size whose elements will be converted in accordance with a predetermined function. [17]

In the thesis MATLAB is used for describing and comparing the data obtained from the Vicon and Kinect systems.

Matlab vector is a sorted list of numbers. In MATLAB you can enter a vector of any length, by entering a list of numbers, separated by commas or lacunas.

In the figures 3.1, 3.2 there are presented the obtained charts of the angles changes between the femur and cnemis:
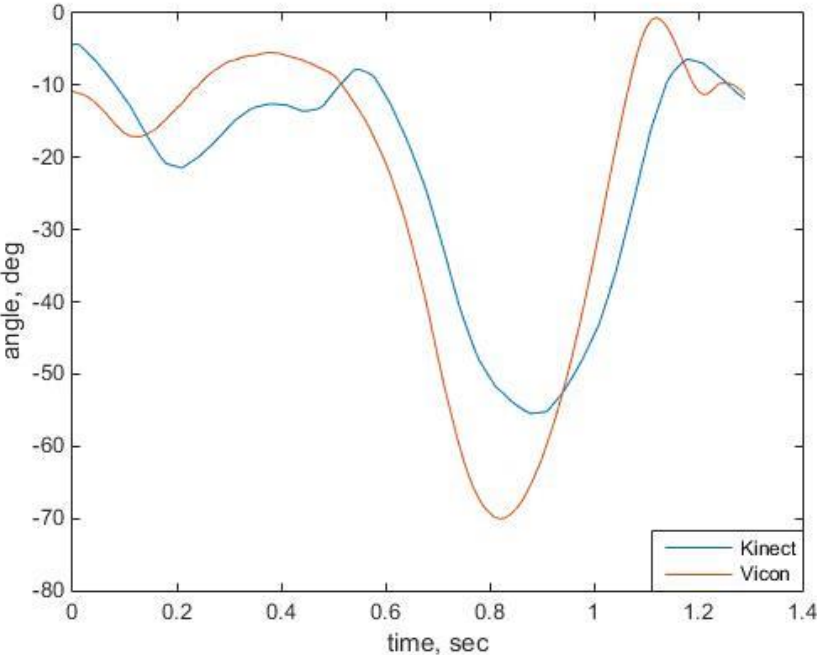

Fig. 3.1. The chart of the angle change between the hip femur and cnemis of the right leg
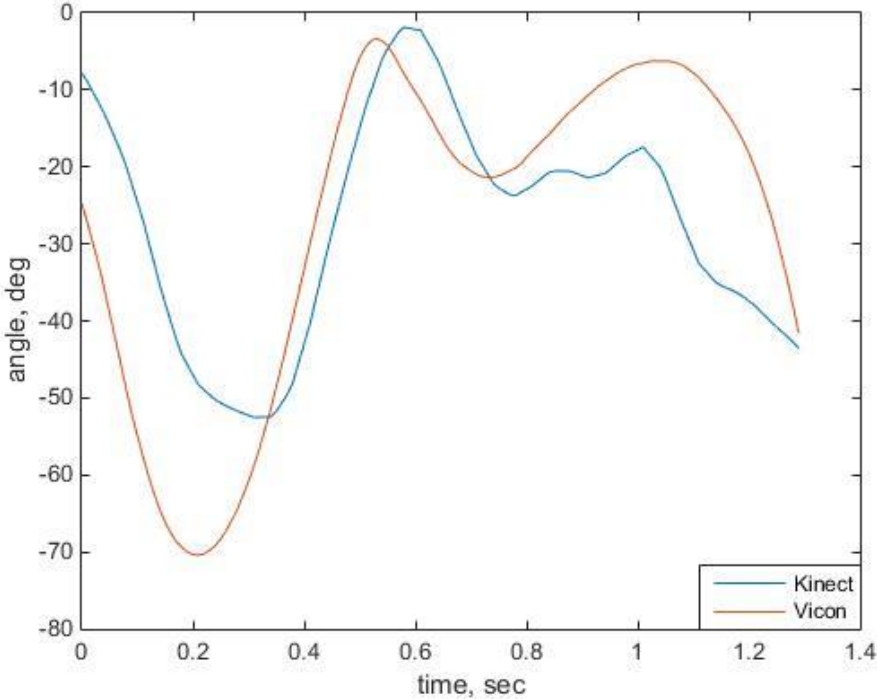
Fig. 3.2. The chart of the angle change between the femur and cnemis of the left leg

On the basis of the data mentioned above we calculate the maximum and minimum values of functions.

As a result we get the following values:

The maximum angle change between the femur and cnemis of the right leg from the data obtained using the Vicon system -0,5929, and the minimum one is -70,0333

The maximum angle change between the femur and cnemis of the right leg from the data obtained with the help of Kinect -4,2461, and the minimum one is -55,4846

The maximum angle change between the femur and cnemis of the left leg from the data obtained using the Vicon system -3,3442, and the minimum one is -70,4092

The maximum angle change between the femur and cnemis of the left leg from the data obtained with the help of Kinect -1,8422, and the minimum one -52.5212
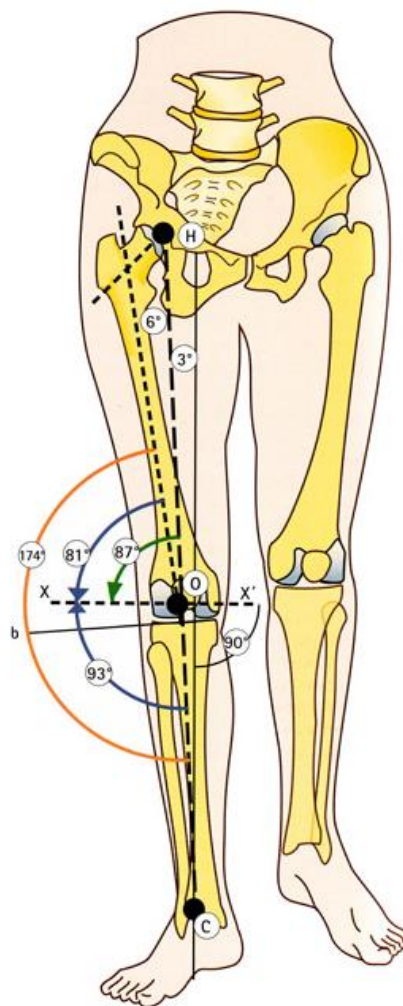

Fig. 3.3. The angles between the femur and cnemis [35]

We compare the obtained data of maximums and minimums with the real possibilities of angle change between the femur and cnemis. As a result we can conclude that the obtained angles are correct.

Next, we compute the standard deviation of the array elements which is calculated according to the formula

$$S = \left(\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right)^{1/2}$$

(3.1)

where x is a vector. [24]

Let's compute with the help of the std command:

The standard deviation of the array elements of the angles between the femur and cnemis of the right leg, received with the help of system Vicon is 21,5655

The standard deviation of the array elements of the angles between the femur and cnemis of the right leg, obtained with the Kinect system is 16,2585

The standard deviation of the array elements of the angles between the femur and cnemis of the left leg, received with the help of system Vicon is 21,1959

The standard deviation of the array elements of the angles between the femur and cnemis of the left leg, received with the help of Kinect is 14,5341

Obviously, the Vicon data scatter is great, but the scatter between the data received by the systems Vicon and Kinect is not significantly large. Therefore, the retrieval of Vicon is the greater standard deviation, it is equal to about 21, and the retrieval of Kinect is less, it is equal to about 15. The difference between them is not very significant, this means that the data does not have great scatter between each other, and it can be analyzed relatively to each other.

Mathematical expectation of discrete random variable is called the sum of products of possible values with corresponding probabilities:

$$M(X) = x_1 p_1 + x_2 p_2 + \ldots + x_п p_п$$

(3.2)

If the number of possible values of a random variable is infinite, then the resulting series converges absolutely.

Dispersion (scattering) of a random variable is called the mathematical expectation of the square of its deviation from its expected value:

$$D(X) = M (X – M(X))^2 \qquad\qquad (3.3)$$

Using the cov command, which returns the dispersion of the array elements, we obtain the coefficients of the dispersion:

The coefficients of dispersion of the angles data between the femur and cnemis of the right leg

D(V)=16,25

D(K)=21,56

The coefficients of dispersion of the angles data between the femur and cnemis of the left leg

D(V)=14,87

D(K)=21,2

Next, we need to obtain the correlation coefficients. For this we use the function corrcoef, which calculates the correlation coefficients.

Correlation is a statistical interaction between two or more random variables. The changes of the values of one or more of these quantities are accompanied by systematic changes in the values of another or other quantities.

Mathematical measure of correlation of two random variables is the correlation coefficient R (or r).

Some types of correlation coefficients can be positive or negative. In the first case it is assumed that we can determine only the presence or absence of connection, while in the second there is the same as well as its directivity. If it is assumed that values of variables are set against the strict order, then a negative correlation is a correlation in which the increase of one variable is associated with the decrease of another. In this case the correlation coefficient will be negative. The positive correlation in such circumstances is such a connection, in which the increase of one variable is associated with the increase of another variable.

The method of calculation of the correlation coefficient depends on the type of the scale, which includes the variables. So, to measure variables with interval and quantitative scales, it is necessary to use the Pearson correlation coefficient (correlation of products moments). If at least one of the two variables has ordinal scale, or is not normally distributed, it is necessary to use the rank correlation or Spearman and Kendall (or Tau) correlation.

The correlation coefficients of the angles data between the femur and cnemis of the right leg is 0,8848

The correlation coefficients of the angles data between the femur and cnemis of the left leg is 0,6869

The correlation coefficients of the angles data between the femur and cnemis have a high value, this means it is possible to use the data obtained with the Kinect system, but with due regard to the mathematical expectation and dispersion.

CONCLUSION

In the work there were considered the methods that currently are used for motion analysis of the lower limbs of the person, as well as the most popular system used for this purpose.

During the formulation of the problem there were selected the motion capture systems: the expensive stationary marker system Vicon, using passive optical markers and 10 optical cameras with infrared emitters, and the cheaper markerless system Kinect.

As a result of the research there was developed to create movements' models of the lower limbs in the software package OpenSim.

Further there was carried out the analysis of the obtained models of the movements of the lower limbs, created with the help of the data received from the motion capture systems Vicon and Kinect with the standard model of OpenSim that takes into account the parameters of the object.

As a result of the study there was developed the algorithm for generating models in the software package OpenSim according to the data, and the algorithm of mathematical analysis to compare the accuracy of the Vicon and Kinect systems. After conducting the mathematical analysis, we can say that the data obtained with the use of the Kinect system, are possible to use, but with regard due to the mathematical expectation and dispersion.

Further, the conducted research can be used in various fields of the film industry, for the possibilities of creating the characters with certain movements, knowing the parameters of actors and using the previously obtained data with the use of the motion capture systems, as well as for rehabilitation in medicine.

FUTURE WORK

This study is the first step in exploring the possibilities of movement modeling with the help of the motion capture systems. The proposed algorithm requires further work to develop more accurate models.

As further work it is necessary to research the peculiarities of muscle skeleton of the lower limbs operation and forces that interact during movement.

After that we will be able to appreciate fully the quality of the models and start to use them not only for medical analysis of patients' rehabilitation, film industry, and multimedia, but also in medical research for identifying the diseases of patients and their treatment.

REFERENCES

1. Все о МОСАР [Электронный ресурс] / Епишин В. // http://www.render.ru/books/show_book.php?book_id=531 (10.03.2016, 08.04.2016).

2. Дубровский В. И., Федорова В. Н. "Биомеханика: Учеб. для сред, и высш. учеб. заведений" — М.: Изд-во ВЛАДОС-ПРЕСС, 2003, 672.

3. Захват движения при помощи технологий компании iPi [Электронный ресурс] / Ильин Ю. // http://old.computerra.ru/terralab/multimedia/532492/ (10.03.2016, 08.04.2016).

4. Использование данных Vicon для моделирования движения в OpenSim// Рубинштейн И.В., Кривцова С.И. (2015) // *Сборник тезисов докладов конгресса молодых ученых.* Электронное издание. – СПБ: Университет ИТМО.

5. Математический анализ данных по захвату движения нижних конечностей человека// Рубинштейн И.В., Кривцова С.И. (2014) *// Сборник тезисов докладов конгресса молодых ученых.* Вып.2. - СПб.: Университет ИТМО, 372-374, 485.

6. Работы в области МОСАР [Электронный ресурс] // http://www.mocaprus.ru/studio.htm (15.03.2016, 20.04.2016).

7. Разработка методики классификации движения нижних конечностей человека с использованием рядов Фурье // Рубинштейн И.В. (2014) // *Аннотированный сборник научно-исследовательских выпускных квалификационных работ бакалавров Университета ИТМО*, 43-45.

8. Разработка и исследование методов захвата, отслеживания и распознавания динамических жестов [Текст]: автореф. дис. канд. техн. наук / Алфимцев А.Н. – Москва: МГТУ им. Н.Э. Баумана, 2008, 18.

9. Распознавание динамических жестов в системе компьютерного зрения на основе медиального представления формы изображений [Текст] : автореф. дис. … канд. техн. наук / Куракин А.В. – Москва: МФТИ, 2012, 22.

10. Чадова М., Галло Л.М. «ПОДХОДИТ ЛИ OPENSIM ДЛЯ АНАЛИЗА ЖЕВАТЕЛЬНОЙ СИСТЕМЫ?» (2013) // ст. *Российский журнал биомеханики*, Т. 17, № 3 (61), 64–81.

11. Экспериментально-модельный подход при исследовании кинематики движения человека// Рубинштейн И.В. (2016) // *Сборник тезисов докладов конгресса молодых ученых*. Электронное издание. – СПБ: Университет ИТМО.

12. Delp, S.L, Андерсон, F.C, Арнольд, A.S, Займа, Р., Хабиб, А., Джон, К.Т, Guendelman E., Thelen, D.G. OpenSim: программного обеспечения с открытым исходным

кодом для создания и анализа динамического моделирования движения. (2007) // *IEEE Transactions на биомедицинской инженерии*, Vol. 55, , 1940-1950.

13. Experimental model approach in the study kinematics of human motion // Рубинштейн И.В. (2016) // *Сборник тезисов докладов конгресса молодых ученых*. Электронное издание. – СПБ: Университет ИТМО.

14. Generating optimized marker-based rigid bodies for optical tracking systems / Steinicke F., Jansen C., Hinrichs K., Vahrenhold J., Schwald B. (2007) *// In 2nd international conference on computer vision theory and applications (VISAPP)*, 387 – 395.

15. High definition motion capture [Электронный ресурс] / M. Orman http://tyrell-innovations-usa.com/shop/index.php?option=com_content&view= article&id=9&Itemid=8 (15.03.2016, 20.04.2016).

16. Hand gesture recognition with depth images: A review / Suarez J., Murphy R. // RO-MAN, 2012 IEEE, P. 411 – 417, 2012.

17. Motion tracking: no silver bullet, but a respectable arsenal / G. Welch, E. Foxlin // IEEE Computer graphics and applications, vol. 22, № 6, 2002, P. 24 – 38.

18. Rubinstein I.V., Musalimov V.M., Lavrov A.V., Chachaeva A.V., Кривцова С.И., Khlebushev L.S., Smolin A.A. Hardware Capturing Analysis and Synthesis of Human Gait (2014) // *Proceedings of the 14th International Symposium Topical Problems in the Field of Electrical and Power Engineering, Doctoral School of Energy and Geotechnology*, January 13-18, 2014, Parnu / Faculty of Power Engineering, Tallin University of Technology, 268-271.

19. The usage of Vicon data for motion modeling via OpenSim// Rubinstein I., Krivtsova S. (2015) // *Closing Conference of the Project "DOCTORAL SCHOOL OF ENERGY AND GEOTECHNOLOGY II"*, 178.

20. The usage of Vicon data for motion modeling via OpenSim// Рубинштейн И.В., Кривцова С.И. (2015) // *Сборник тезисов докладов конгресса молодых ученых*. Электронное издание. – СПБ: Университет ИТМО.

21. http://www.docme.ru/doc/900528/referat---mgtu-im.-n.-e-.-baumana (16.03.2016, 20.04.2016).

22. http://www.bestreferat.ru/referat-401678.html (16.03.2016, 20.04.2016).

23. http://www.svga.ru/article_info.php?articles_id=96 (16.03.2016, 20.04.2016).

24. MATLAB. Полный самоучитель // Владимир Дьяконов // ДМК-Пресс, 2014 г.

25. http://biomechanics.pro/node/341 (10.03.2016, 08.04.2016).

26. http://render.ru/books/show_book.php?book_id=600 (10.03.2016, 08.04.2016).

27.   http://club.cnews.ru/blogs/entry/programmnyj_paket_vicon_blade_2_dlya_otsifrovki_ dvizhenij_obekta (10.03.2016, 08.04.2016).

28.   http://www.softrew.ru/obzory/windows/1354-kinect-2-dlya-windows-evolyuciya-beskontaktnogo-kontrollera.html (10.03.2016, 08.04.2016).

29.   http://habrahabr.ru/post/151131/ (10.03.2016, 08.04.2016).

30.   http://xbox360help.com.ua/kinect+windows.html (10.03.2016, 08.04.2016).

31.   http://habrahabr.ru/post/142236/ (10.03.2016, 08.04.2016).

32.   http://vm.psati.ru/online-tv/page-07.html (10.03.2016, 08.04.2016).

33.
http://www.ugatu.ac.ru/assets/files/documents/dissov/07/2014/KotyuzhanskiiLA/Kotyuzhans kii.pdf#4 1.   (10.03.2016, 08.04.2016).