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Department of Mechatronics

Chair of Mechanosystem components

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Orthosis supported human lower limb motion model

Master's Thesis

Author applying for
master's sciences of technical
academic degrees

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AUTHOR'S DECLARATION

I declare that I have written this graduation thesis independently. These materials have not been submitted for any academic degree. All the works of other authors used in this thesis have been referenced.

The thesis was completed under .... supervision

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Author

.... signature

The thesis complies with the requirements for graduation theses.

“.......”....................201….a.

Supervisor

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Accepted for defence.

.... chairman of the defence committee´

“.......”....................201… a.

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TUT Department of Mechatronics
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MASTER'S THESIS TASK

Year 2016 Spring semester

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MASTER'S THESIS TOPIC:
(in English) Motion modeling of the human lower limb, supported by orthosis.
(in Estonian) Ortoosiga toetatud inimese jala liikumise modelleerimine

Assignments to be completed and the schedule for their completion:

Nr	Description of the assignment	Completion date
1.	Overview of the counterparts in the areas of knee joint modeling. Formulating requirements to the knee joint model. Creation simple model of the knee joint.	**01.02.2016**
2.	Making experiments with using inertial system and passive motion capture system. Comparer the results of this experiments. Static, kinematic analyze of the knee joint.	**01.03.2016**
3.	Creating model of the system: human leg-leg support.	**01.04.2016**
4.	Analyzing and optimization model of the system: human leg-leg support.	**30.04.2016**
5.	Printing and binding of Master's thesis.	**15.05.2016**

Engineering and economic problems to be solved: In this master's thesis the model of the system: human leg-leg support has to be developed. The main aim of this thesis is making model, which allow model interaction between human leg and leg support.

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

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Deadline for submitting the theses 16.05.2016

Student Nadezhda Krokhaleva /signature/ ………...............date 09.02.2016

Supervisor Igor Penkov /signature/ ………................ date 09.02.2016

Supervisor Gennady Aryassov /signature/ ………................ date 09.02.2016

Confidentiality requirements and other corporate terms and conditions shall be set out on the reverse side.

TABLE OF CONTENTS

FOREWORD

This thesis was written within the framework of master's double degree program between Tallinn University of Technology and ITMO University. This work is continuance in some degree my bachelor's research, which was been refined in accordance with the specific of this double degree programs.

This thesis was written in Tallinn University of Technology. Experiments aimed at receiving of reference data for model which created within the framework of this thesis were carried out on the basis of the St. Petersburg Institute of Cinema and Television.

I wish to express appreciation to departments of mechatronics of Tallinn University of Technology and departments of mechatronics of ITMO University for this very useful experience. Also I wish to express appreciation to all collaborators of this departments which always were ready to help. Especially I want to express thanks to my supervisors: Igor Penkov and Gennady Arayssov from Tallinn University of Technology and Stanislav Reznikov from ITMO University for valuables advises. Besides I want to express appreciation to Svetlana Perepelkina for her patience, support and tips.

EESSÕNA

See magistritöö oli kirjutatud Double degree MSc Mechtronics programmi raames. Selle programmi raames Tallinna Tehnikaülikool (TTÜ) teeb koostööd Sankt-Peterburgi Informatsioonitehnoloogiate, Mehaanika ja Optika Ülikooliga (ITMO). Magistritöö on minu bakalaureusetööga seotud uurimistöö edasiarendus, mis vastab Double degree MSs Mechtronics programmi nõuetele.

See magistritöö oli kirjutatud Tallinna Tehnikaülikoolis. Töö eksperimentaalne osa, mis hõlmab endasse andmete kogumist mudeli koostamiseks, oli teostatud aga Sankt-Peterburgi Filmi ja Televisiooni Instituudis.

Ma tahan avaldada tänu TTÜ Mehhatroonikainstituudile ja ITMO–le selle meeldiva kogemuse eest. Ma tänan kõiki nende instituutide töötajaid, kes olid alati abivalmis. Eriti tahaks tänada minu juhendajaid: Igor Penkov ja Gennadi Arjassov TTÜ-st ning Stanislav Reznikov ITMO-st nende soovituste, märkuste ja näpunäidete eest. Lisaks soovin tänada Svetlana Perepelkina toetuse ja kasulike näpunäidete eest.

1. INTRODACTION

Knee joint is one of the most difficult joints from the point of biomechanics [1]. Knee joint is a movable connection of the femur, tibia, fibula and patella. Also meniscus, capsular-ligamentous apparatus and muscle-tendinous complexes are included in the knee joint. Knee joint has six degrees of freedom: it can rotate and move in three planes. That makes studying of the knee joint more difficult, because of having occasion to resort tosimplifications which makes imprint on the accuracy of the data which were got during research.

Knee joint is one of the most complex and vulnerable joints in the human's musculoskeletal system. This caused by the fact that at this point articulate the longest levers of the lower limb: the femur and tibia. Almost every person in explicit or implicit form faces with injuries of the knee joint. These injuries can proceed unnoticed, or may confined to bed. Orthoses are used for rehabilitation after knee joint injuries very often, but choosing of orthosis is laborious process, which takes a lot of time [2].

For knee joint researching, modeling are often used, but because of the knee joint complexity, authors simplify models. There are a lot of models of the knee joint which simulate parameters of the knee joint in different degrees, depending of research. It can be two-dimensional planar mechanism with four or six links; model, where three successive rotates of the knee joint are considered; model, with six degrees of freedom, where bone's surfaces were obtained by direct measurement. Model of the knee joint, supported by passive orthosis [3-7].

Purpose of this thesis – creating model which imitates motion of the knee joint supported by orthoses. Model considered in this research is relevant because it allows to simplify the selection of the orthosis and avoid possible complications. Besides, such models have not been found during the review of analogues.

The first chapter introduces little background to the work, its purpose, and short content.

The second chapter describes the features of the knee joint anatomical structure, the most common injuries of the knee joint, little overview of post traumatic period was made.

In the third chapter trajectory of motion of the knee joint elements were considered, namely, tibia and patella motions around the femur.

In the fourth chapter there is a brief overview of the motion capture. Choosing the most suitable method of motion capture for this research. Described and analyzed experiments conducted using the selected methods of motion capture.

The fifth chapter is a brief overview of existing models of the knee joint. Design of the model created in this research was described. Furthermore, the design of model was analyzed in terms of kinematics.

The sixth chapter describes creation model of the knee joint, supported orthosis in MATLAB. In this research, a model created based orthosis developed by Nikita Turchinovich during work on the thesis «Design of knee joint support system» was consider.

The seventh chapter presents and analyzes the results of the model developed in this research.

In conclusion, the analysis of the work was made, analyze of the results of the model was made also and possible future directions of work was described.

2. STATE OF THE QUESTION

2.1. Knee joint

Knee joint is a part of human locomotor system. Knee joint is the most tense and complex from point of biomechanics. It is most vulnerable at human musculoskeletal system. This caused by the fact that at this point articulate the longest levers of the lower limb: the femur and tibia. In the formation of the knee joint in addition to the distal end of the femur and the proximal end of the tibia are participating fibula, patella, meniscus, ligaments, muscles and tendons of the knee. Knee joint is shown in Figure 2.1 [8].

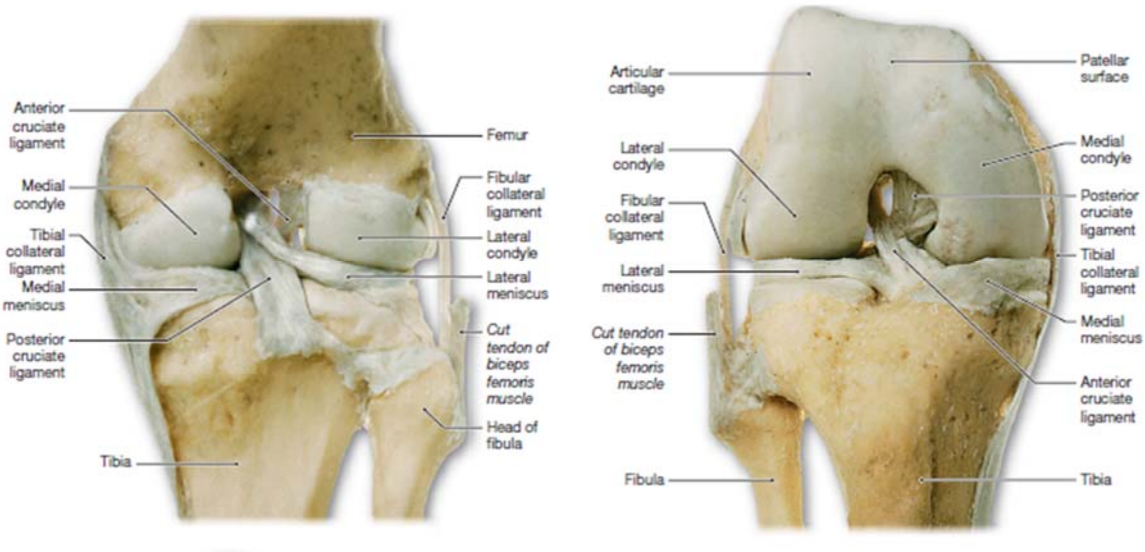


Figure 2.1. Right humans knee joint [9].

Around the knee joint the joint capsule is formed. Joint capsule - hermetically sealed cavity, which located at the place of bones attachment. Joint capsule has a small cleft filled with serous fluid.

Femoral's condyles, which are connected to the tibia in the transverse and sagittal planes are segments of an ellipsoid, covered with cartilage. Condyles of the tibia, connected with the condyles of the femur are two weakly upwards platforms, covered with hyaline cartilage.

Meniscus (cartilages inside of joints) are situated between condyles. Meniscus are kind of spacers between the femur and the tibia. They participate in depreciation and redistributing of the bearing loads on the surface of the joint's bones, they stabilize the joint and promote of the synovial fluid movement. (Bursa, which filled with synovial fluid is located between meniscus). Meniscus associated with the joint capsule, by the periphery with meniscus-femoral and meniscus-tibial (coronary) ligaments. Meniscus move together with the condyles of the tibia. They have a close relationship with each other, with collateral ligaments and cruciate ligaments.

Cruciate ligament are located inside of the joint, they separated from knee joint's cavity with help of synovial membrane. Average thickness of ligament is 10 mm, length - 35 mm. It is attached to the posterior part of the internal surface of the of the outer condyle of the femur by wide base, then, following the referral down, inward and forward, it is attached at the front intercondylar eminence of the tibia.

Ligaments are a plurality of fibers, conventionally separated into two beams. This separation is intended for explaining of the functioning of the ligaments for joint's different positions. Considered that at full extension the main load in anterior cruciate ligament fall at posterolateral bundle and during the flexion - anteromedial bundle. As a result, a bundle in any position of joint retains its working tension. The main function of the anterior cruciate ligament - a prevention of external subluxation of the tibia's lateral condyle at the most vulnerable position of the joint.

The posterior cruciate ligament begins in the anterior part of the internal surface condyle of the femur than, following back down and out, it's attached in area of the posterior intercondylar fossa of the tibia. Some of the posterior cruciate ligament fibers are attached in the posterior part of the joint capsule. Posterior cruciate ligament has a thickness of about 15 mm and a length of 30 mm. Ligament is separated into two beams, the main beam - anterolateral and less important beam - posteromedial. The main function of the posterior cruciate ligament - a prevention hyperextension of the tibia.

The medial collateral ligament is the primary stabilizer of the knee joint on it's inner surface. The main function of the medial collateral ligament - preventing deviation of the tibia and preventing of front subluxation of the medial condyle. The medial collateral ligament separated into two parts: superficial and deep. The superficial part implements a stabilizing function mostly. It contains long fibers which spreads fan-shapedly from internal epicondyle of the femur to the medial parts of the tibia. Deep part consists of short fibers associated with medial meniscus and forming meniscus-femoral and tibial-meniscus ligament. Behind of the medial collateral ligament posteromedial part of the capsule is located, it is playing a significant role in stabilizing the joint.

Lateral and posterolateral parts of capsular-ligamentous apparatus are set of ligament-tendon structures, naming posterolateral ligament-tendon complex. Posterolateral ligament-tendon complex includes: the posterolateral structures, the lateral, collateral ligaments and tendon of the biceps femoris. Under the posterolateral structures imply an arcuate ligaments complex, hamstring and popliteal-fibula ligament. Main function of complex - stabilization posterolateral parts of the knee joint, obstacle deflection of tibia and obstacle of rear subluxation of the lateral condyle of the tibia.

Dynamic stabilizers of the knee joint include three groups of muscles, which are located on the front and side of its surfaces. As synergists for certain capsular-ligamentous structures, they are particularly important during a temporary or permanent failure of capsular-ligamentous structures after recent injuries or reconstructive operations [10].

2.2. Injuries of the knee joint

A lot of people face with the problems of the knee. Most often, these injuries are the a result of knee strikes, landing on a straight leg during a jump from a height, over-extension of the knee joint. All damage to the knee joint have the following symptoms: bleeding in the joints, swelling, pain, the so-called "loosening of the patella", and during the fracture of the patella - separating on two or more number of parts.

Main injuries of the knee joint:

Injuries of the meniscus,

Injuries of the ligaments,

Intra-articular fractures (fractures of the condyles of the femur or tibia, intercondylar eminence of the tibia and fracture of the patella)

All injuries of the knee joint can be combined [11].

For example of the knee joint injuries consider injuries of the ligaments, shown in Figure 2.2 – one of the injuries, which rehabilitation period much heavier than operation. Person's ability to walk depends from rehabilitation period.

Athletes after such injuries end a career very often and sometimes become disabled. However, in everyday life rarely occur loadings on the knee with such force that they can damage the ligaments. In addition, with proper care and appointment of the procedures , with a probability close to unity, people can not only walk, but return to sports activity also.

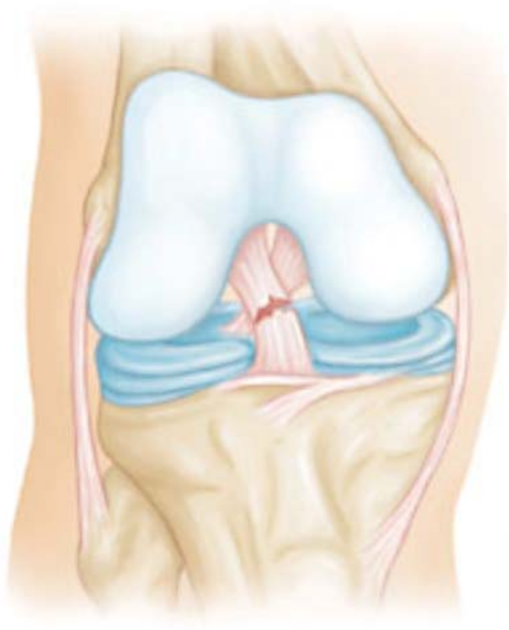


Figure 2.2. Circular ligament rupture [12].

Equally common are chronic diseases. They are often the consequence of the fact that the treatment of injury or infection of the knee was performed incorrectly or incompletely. The most common chronic form of the disease are:

• arthritis and arthrosis (the main feature - the periodic bouts of pain and limited of the movement)

• osteoporosis (main symptoms - aches in the bones and joints in response to changes in the weather, as well as the permanent or periodic discomfort in the knee joint caused by cartilage wears.)

• chondromalacia patella (main symptoms - pain between the patella and femur)

• gout (basic signs - durational (up to 7 days) periodic painful attacks that cause swelling of the ligaments and tendons of the knee joint [13].

Let us consider in more detail one of the chronic diseases of the knee joint – arthrosis, which shown in Figure 2.3, cartilage wears away over time, it leads to serious violations of the knee, which are irreversible.

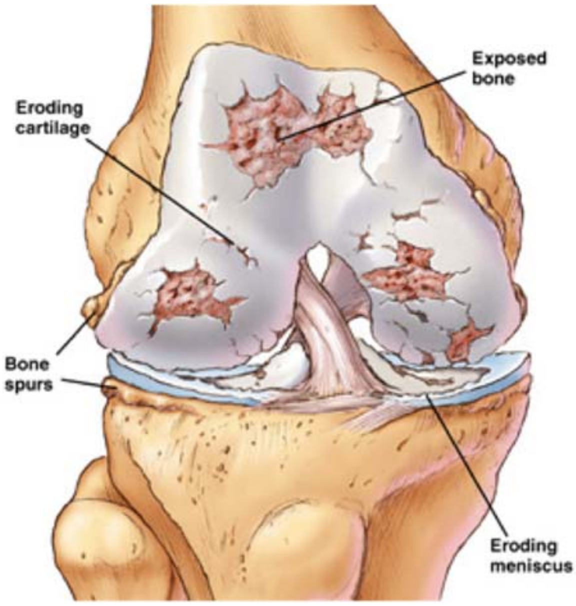


Figure 2.3. Arthrosis of the knee joint[14].

Given the current development of science, cartilage replacement is possible, however, this operation is expensive and does not give an absolute guarantee. Operating method has one more disadvantage: age limit. In the cases that the likelihood of the successful outcome of the operation will be very small compared with the effects - this method can't be used [15].

2.3. Post-traumatically period

Injuries of the knee are dangerous by themselves, and during the rehabilitation period. Doctors cannot predict outcome of one or another injury unambiguously. The treatment of the knee joint is utmost laborious process. It demands special skills, knowledge, as well as skills of combining up-to-date investigations of the knee joint and experience in treatment of the knee, besides any little inaccuracy in the performance of doctors recommendations during post-surgical period is able to lead to catastrophic outcomes.

Rehabilitation after knee injuries is long and monotonous process. Special attachments can alleviate this process, for example orthoses and exoskeletons, created to help muscles not to atrophy or adapt after operations. Main function of orthoses and exoskeletons are supporting function and protective function. Orthoses help to unload the knee at the place where it is necessary or detent them for some time, and also restore the work of muscles. Orthoses are divided into active and passive, passive orthoses do not have a power source and operate thanks to the efforts of the operator, while active orthoses use additional motors for motion.

In addition to the advantages of orthoses they have a major drawback: the orthoses made for individual sketch has a high cost, but orthoses in mass production, require serious individualization. The process occurs of the discretion of the physician, and therefore even a small extra degree of freedom can lead to the fact that the orthosis will add loads at the point where knee joint was damaged, which may lead to irreversible consequences.

2.4. Conclusion

The knee joint is the most complex and vulnerable joint in the human's musculoskeletal system. Almost every person in explicit or implicit form faces with injuries of the knee joint therefore it is important to investigate knee joint for determining distribute of loads and how they can be compensated, or weakened at least. In addition, investigation of the knee joint structure will allow facilitate the treatment of injuries and rehabilitation after them.

Analysis of the most common injuries showed that the knee injuries are dangerous by themselves, and during the rehabilitation period.

During the rehabilitation period passive and active orthoses are often used, but the selection and fitting of orthoses is long and laborious process, therefore place of fixing, type and design of the orthosis should have a significant impact on the model of the knee joint, supported by orthosis.

3. FEATURES OF THE MOVEMENTS OF THE KNEE JOINT ELEMENTS

3.1. Movement trajectory of the tibia around femur

The rotational motion of the knee in the sagittal plane is performed between the articular surfaces of the condyles of the femur and tibia and is associated with the movement "sliding-rolling." During this movement articular surface of the tibia's condyles pass along a difficult trajectory of movement around articular surfaces of the condyles femur, differing among themselves in size and radius of curvature. Described curve of the movement trajectory between the articular surfaces of the condyles of the femur and the tibia was named «vertex cubis».

Figure 3.1 illustrates the amplitude and direction of movement of the condyles of the femur and tibia at maximum flexion of the knee.

a) b) c)

Figure 3.1. Moving of the condyles of the tibia relative to femoral condyle. a - position of extension; b - flexion 90 ° c - maximum flexion in the joint [16].

At full extension of the knee femoral condyle will situated in a few anteriorly relatively femoral condyle (Figure 3.1.a.), during flexion on 90 ° - a slight extension of the condyles of the tibia anteriorly to the femur (Figure 3.1.b.). At maximum flexion - extension of the condyles of the tibia relative anterior to femoral condyles of 10 mm with internal rotation around the vertical axis. The movement and layering of the fibula on the tibia, and the outer condyle of the tibia extends anteriorly (Fig 3.1.c.) [16].

This movement is due of the presence cruciate ligament in the knee joint. Provisions of the tibia relative to the femur caused by the position of the cruciate ligament is shown in Figure 3.2.

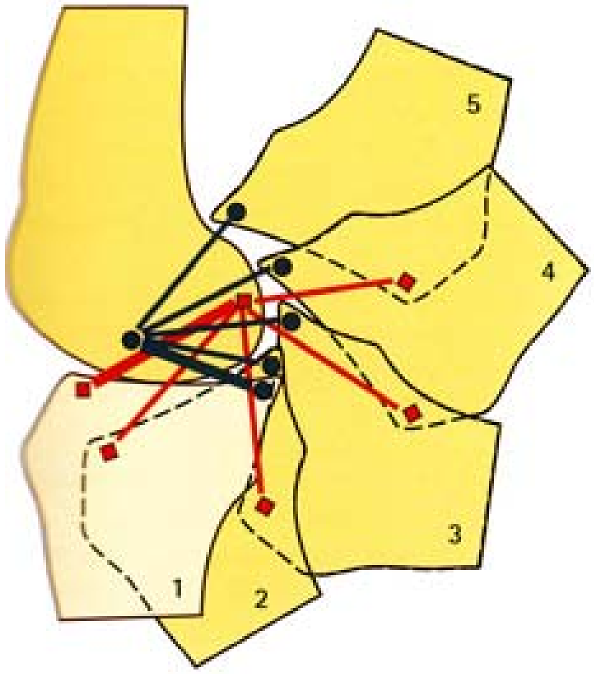


Figure 3.2. The provisions of the tibia relative to the femur during rotation [17].

By varying the geometric relationships in the system of the cruciate ligament, a whole array of arcs for the condyles and the block can be traced. This highlights the uniqueness of each knee. Judging from the standpoint of geometry, there are no two identical knee joints, therefore a selection process of orthosis consuming a lot of time [17].

3.2. Movement trajectory of the patella around femur

During flexion and extension patella moves in the sagittal plane. Beginning from the position of full extension, it steps back, making a circular motion centered on the tibial's tuberosity. Radius of this circular motion equal to the length of the patellar tendon. During this movement, the patella is bends over by about 35 ° so that its back surface in initially position rotated back, at full flexion is rotated back and downward. Thus, the patella performs rotary motion around the tibia , this motion is represented in Figure 3.3.

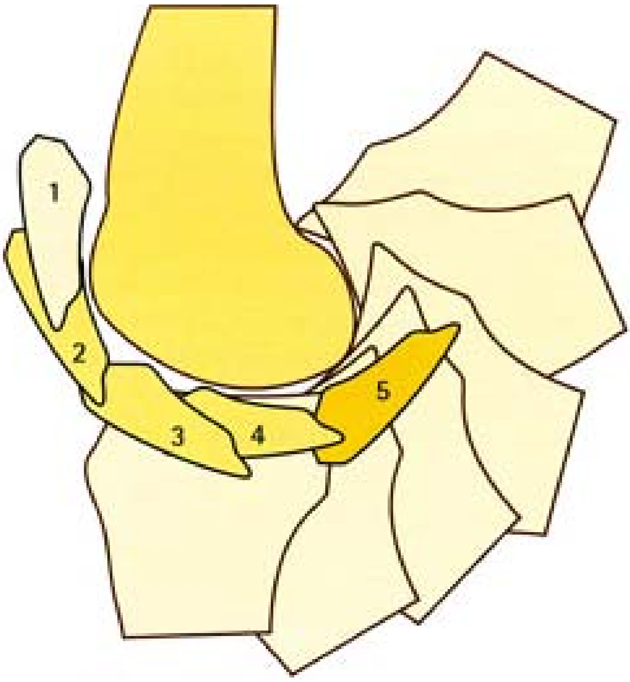


Figure 3.3. The provisions of the patella during movement around the femur [17].

This movement of patella occurs by cause following two mechanisms: the offset posteriorly points of contact between the condyles of the femur and tibia; reducing the distance separating of the patella from the flexion / extension axis [17].

Extension of the knee joint is realized by means of the extensor apparatus, it is: the tendon of the quadriceps, the patella and patellar ligament [18]. Knee's extensor apparatus slides by the distal end of the femur, as by direct. Block femur and intercondylar notch create a deep vertical groove, in depth of which slides patella. Thus the strength of the quadriceps, which directed obliquely upwards and slightly outwards, turning into a strictly vertical force. Therefore, the normal movement of the patella relative to the femur during the flexion it is a vertical displacement along the central sulcus on the block of the thigh to the intercondylar notch. The movement of the patella is shown in Figure 3.4 [19]. The patella moves downward by a distance equal to its two lengths (about 8 cm), turning with respect of its transverse axis. When the patella at the end of the its movement (full flexion) it is located under the femoral condyles, lateral surfaces of patella, which during extension is oriented directly posteriorly, rotated upwards. Thus, this movement can be called as rotation movement around the femoral [17].

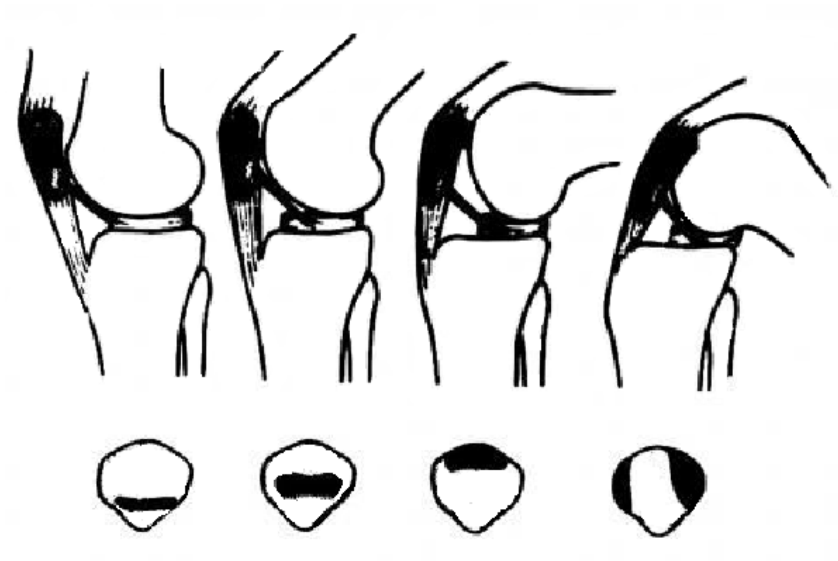


Figure 3.4. Position of the patella depending by the flexion angle of the knee joint [19].

3.3. Conclusion

The trajectory of movement of the tibia relative to the femur caused by the presence of a cruciate ligament, therefore, in addition to the tibia and femur it is necessary to simulate the cruciate ligaments.

Patellar movement is provided by extensor mechanism therefore it is necessary to simulate patella, patellar ligament, quadriceps tendon and quadriceps. Also it is necessary to note that patella rotates around the femur and around the tibia.

In addition, it is very important to take into account the variability of the model. For this purpose all the simulated parts of the knee should have changeable parameters.

4. MOTION CAPTURE METHODS FOR GETTING AND ANALYZING EXPERIMENTAL DATA

4.1. Motion capture methods

At this moment a lot of motion capture methods which are used in different areas of science are existed. However frequently data capture performed by only one method, it significantly reduces efficiency of data capture. During investigation of motion capture methods, four methods which are the most appropriate, in the framework of the objectives were chosen.

- The photographic method is used for determining of points of trajectory. Measurements by this method require a digital camera and markers which can help tracking of point position better. In addition for calibration of camera requires special calibration grid. The method is shown on the figure 4.1 [20].

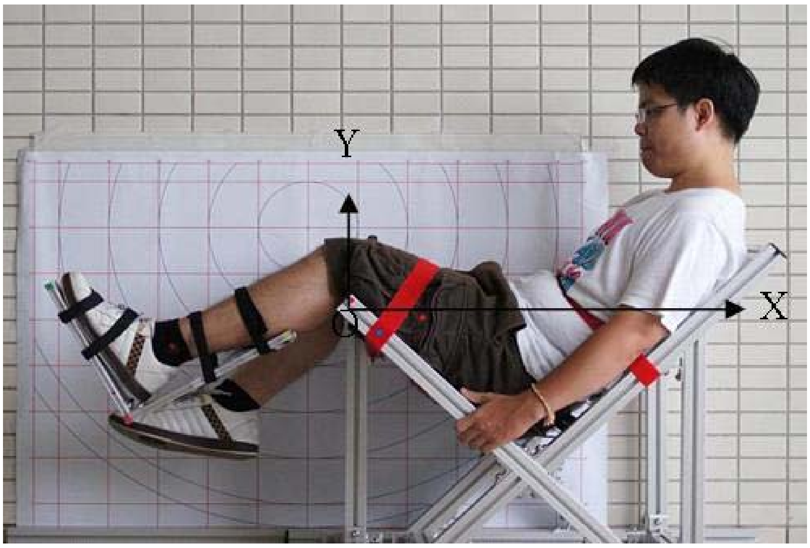


Figure 4.1. Photographic Method [20].

- Optical motion capture produced with the help of several cameras which located in different places and from different angles. During data processing data obtained from each camera and cameras position takes in account. The program brings together information about camera position and the image which obtained from it, and determines how the object moves in space. Moving of the objects is determined relative to a room or relative to set point.
- Most optical systems used markers which affixed to the object. The markers may be active they emitting light or passive they reflect light. Additionally, there are systems which do not require the markers, they give less accurate data but they more convenient in some cases. The method is shown in Figure 4.2.

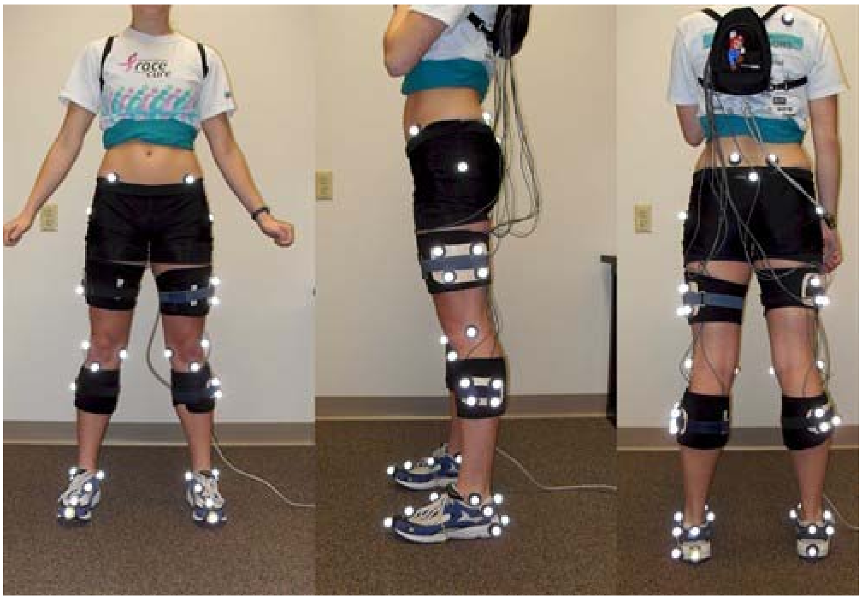


Figure 4.2. Passive optical motion capture system [21].

- The method which uses inertial sensors. For experiments with this method are required inertial sensors and controller for their software, often in inertial systems also used gyroscopes. Accelerometers measured acceleration in one, two or three planes, while gyros determined the orientation of the sensor in space. Based on the readings of accelerometers and gyroscopes the acceleration and it's direction can be determined [22]. An example of the inertial system is shown in Figure 4.3.

Figure 4.3. Suit with 17 inertial sensor modules [23].

- The method which uses magnetic sensors. Motion capture is performed using the electromagnetic field generators and special sensors. Using this methods, the change in the three coordinate axes of the magnetic field generated by the magnetic field generator is measured. For orientation in three-dimensional space changing of the magnetic-field vectors are recorded . Capturing data using magnetic sensors is shown in Figure 4.4. [24-25].

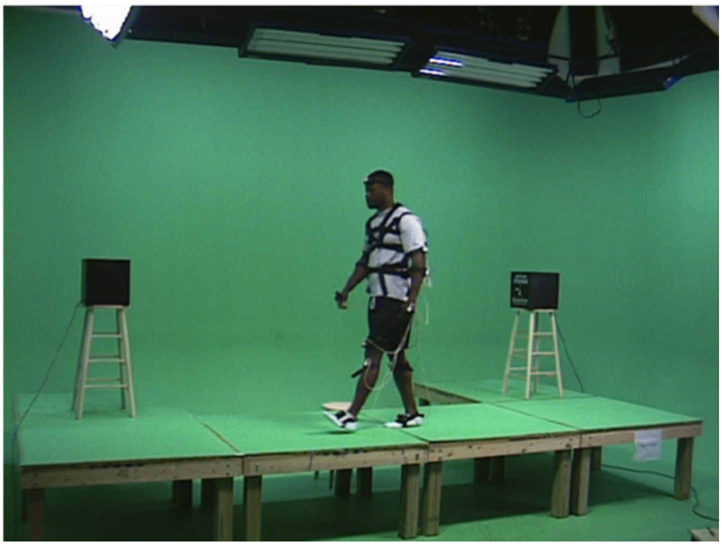


Figure 4.4. Method with using magnetic sensors [25].

At the table 4.1. result of the methods comparison is represented.

Table 4.1. Comparison of the motion capture methods

Method / Criteria	Photographic Method	Method with using passive optical motion capture system	Method with using inertial system	Method based on electrical activity of muscles
Mobility	High	Low	High	Middle
Accuracy	Middle	High	High	Low
Working area	Middle	Middle	Big	Small
Loosing of the markers	Middle	High	-	-
Needing for additional processing	Yes	Yes	Yes	Yes

During the research, experiments using inertial sensors and passive optical motion capture system were performed. These methods were selected as the most available and suitable in terms of accuracy.

4.2. Passive optical motion capture system VICON

4.2.1. VICON Bonita

VICON Bonita – is infrared camera which is used in passive optical motion capture systems. Using the camera VICON Bonita, and a software package VICON Blade, allows to create optical systems capable for receiving data.

Camera of model Bonita 10 is shown in Figure 4.5. It characteristics are shown in Table 4.2. [26-27].

Figure 4.5. Camera which is used in passive optical motion capture systems.

Model: Bonita 10 [26].

Table 4.2. Characteristic of the camera Bonita 10 [26-27].

Dimensions	122x80x79 mm
The weight	0,3 kg
Communication interface	Gigabit Ethernet, RJ45
Response	2 ms
Backlight	Infrared strobe: 68 LEDs near-infrared range (780 nm)
Power supply	PoE (Power over Ethernet)
The frequency of the camera	250 fps
Resolution (Megapixels)	1.0
Operating distance	13 m
Viewing angle	26°-70° (caused by a lens with a variable focal length)
Positioning accuracy	0.5 mm

Floor is a square with a side of 5 m, where 10 cameras located on the perimeter , however, because the cameras located at the same level, and the focal length of the cameras constantly the real working area of this system is square with sides of 3 meter. Each camera is equipped with infrared LEDs for illumination markers, established on humans.

Motion capturing performed in costume which made of an elastic material. In addition costume includes gloves on your hands and foots, as well as a cap. 52 markers are attached to the costume with the help of textile fasteners. Markers are located on the joints and large planes, they help to build three-dimensional framework according to the markers.

4.2.1. VICON Blade

VICON Blade – a software package of VICON which is designed to work with motion capture systems. VICON Blade is a comprehensive solution that includes all the tools needed for capturing of the object by markers fixed on object in real time. VICON Blade can control cameras VICON, handle 2D data, which come from the cameras for creating 3D-reconstruction of the space, and for creating kinematic models of biomechanical objects. VICON Blade uses its own scripts written using the HSL language (HeroScript Language) that gives him more flexibility.

Working with VICON Blade can be separated on following steps:

- The preliminary stage. This stage ensures the accuracy of subsequent measurements. It includes creation of the project, determining all of the necessary variables and calibration of the cameras.
- Definition and calibration of the human skeleton. At this stage the person is in the center of the stage and take on a pose for the calibration of the skeleton. In this position, feet are shoulder width apart and arms out to the sides. This position is represented on the figure 4.6.

Figure 4.6. Pose for the calibration of the skeleton [28].

In this position, the markers are determined uniquely, it provide quick transfer of them at 3D-representation of the skeleton inside VICON Blade software.

- Motion Capture. After calibration markers actor may perform any movement within the work zone cameras.
- Post-processing of data obtained during the motion capture. During the motion capture, there are cases when there is a loss of data from markers. These losses can be corrected by using Quick Post or manually. Manually correcting of the data is laborious and takes a lot of time, but the data restored by this way is better than the data recovered using Quick Post technology.

Post-processing of the motion capture allows to restore virtually all data which were lost during the motion capture. After post-processing, the data obtained by the motion capture ready for export and can be used for analysis.

4.3. Motion capture system with using inertial sensors (accelerometers)

4.3.1. The board Arduino MEGA 2560

Motion capture system with using inertial sensors was created based on the board Arduino MEGA 2560, this board is represented on the figure 4.7., it's characteristics are shown in the table 4.3 [29].

Figure 4.7 Arduino MEGA 2560 [29].

The main aim of board Arduino MEGA 2560 – controlling of accelerometers for simultaneous acquisition of data from multiple points. Nine analog ports were used to connect accelerometers to the board. During the experiment board connects to a computer via a USB port for data processing in real time.

Table 4.3. Technical characteristics of Arduino MEGA 2560 [29].

Microcontroller	ATmega2560
Input Voltage	7-12B
Operating Voltage	5B
DC Current for 5V Pin	800 mA
DC Current for 3.3V Pin	50 mA
Digital I/O Pins	54 (of which 15 provide PWM output)

Clock Speed	16 MHz
Analog Input Pins	16
Flash Memory	256 KB of which 8 KB used by bootloader
SRAM	8 KB
EEPROM	4 KB
Length	101.52 mm
Width	53.3 mm
Weight	37 g

4.3.2. Accelerations gy-61

In experiments with using inertial system three-axis analog accelerometers at the scheme ADXL335 have been used, this accelerometers is shown on the figure 4.8.

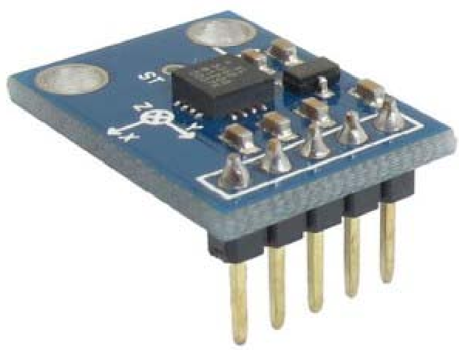


Figure 4.8. GY-61 ADXL335. Three-axis analog accelerometers [30].

Three-axis accelerometer ADXL335 allows to determine linear acceleration in three planes, and measures the angles. Used accelerometer is analog accelerometer, it allows to work separately with each of the axes. Characteristics of the accelerometer are shown in Table 4.4 [30].

Table 4.4. Features Accelerometer GY-61 [30].

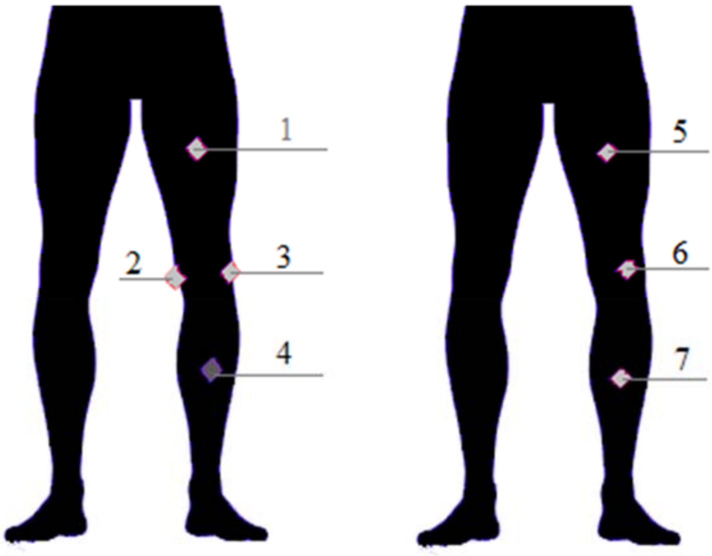
Supply voltage	3-5V
Measurement range	+/- 3g
Sensitivity	300 mv/g

Accuracy	10%
DC Current	400 mA
Dimensions	2,1 mm x 1,6 mm x 1,1 mm
Mass	2 g

4.4. Getting, processing and analyzing of the experimental data

Experiments were carried out on the basis of the St. Petersburg Institute of Cinema and Television. The optical system includes 10 cameras of model Bonita 10 (Fig. 4.5). Inertial motion capture system was established in the framework of this study. This system is based on the Arduino MEGA board in 2560 (Fig. 4.7) with using three accelerometers, gy-61(Fig. 4.8).

During of the experiment, each person from experimental group performed several tasks, such as walking in a circle and walk in a straight line. During the experiments using optical method was used VICON system with 10 cameras Bonita 10, locations of the markers for optical system are shown in Fig. 4.9, a, (point 4 is on the back of the leg). During the experiments using inertial system, was used three accelerometers gy-61 and the board Arduino MEGA, the location of the inertial system's sensors system in the leg is shown in Fig. 4.9, b.



a) b)

Figure 4.9. Location of the markers and accelerometers. Location of the optical system’s markers (a), location of the accelerometers (b)

Data obtained by different methods were processed at MATLAB.

Processing of the data obtained by inertial system:

- Export of the data. Data obtained by inertial systems are exported at MATLAB.
- Filtering of the data. Data filtering is necessary for exclusion of high frequency noise. For this purpose a Butterworth filter is used. Filtration should be implemented first in one direction, then in reverse direction to avoid the phase shift. Comparison of the filtered and input data received from the sensor 7 (Figure 4.9) is shown in Figure 4.10.

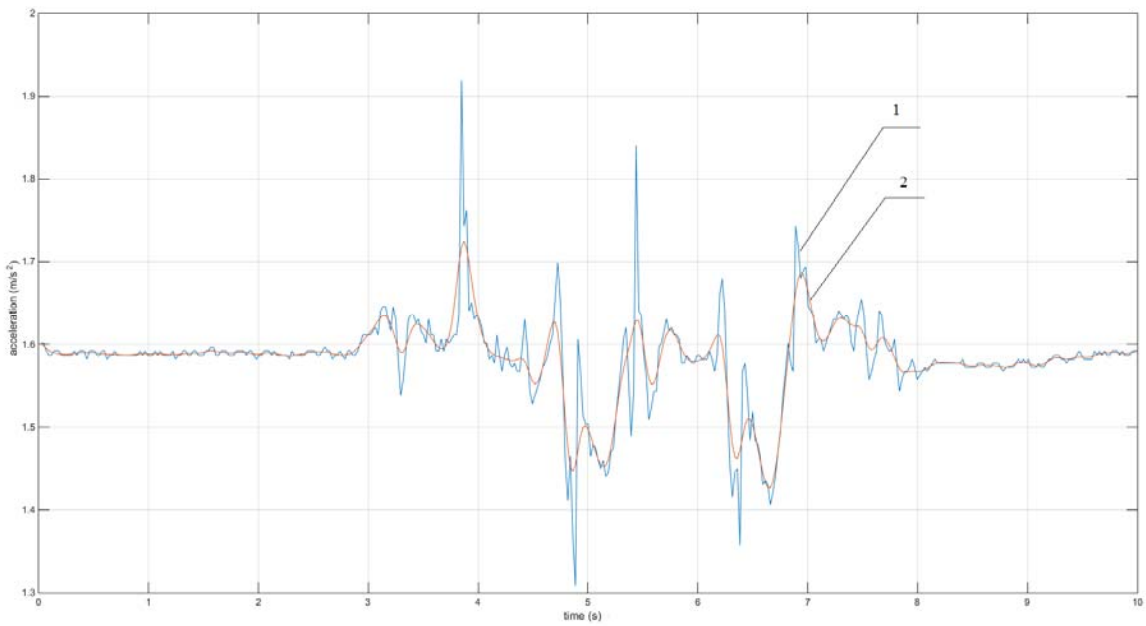


Figure 4.10. Filtering of the data. Line 1 – data received from the sensor 7; line 2 – filtered data.

On this graph line 1 (blue) represents data received from the sensor 7 and line 2 (red) – shows filtered data.

- Segmentation data. At this stage from the overall data array, data necessary for the analysis were selected. In this research examines three full cycles of the step.
- Integration of the data. Since accelerations were obtained using accelerometers, it is necessary to integrate data two times, because by this way displacement of location point's of accelerometers can be got.
- Data Visualization. At this step, graph of accelerated, graphs of found speed and found trajectory of the points were visualized.

Data by Inertial system obtained as a result of processing are shown in Figure 4.11, Yellow line shows the acceleration obtained during the motion capture, the red and blue lines represent velocity and displacement respectively obtained by integration.

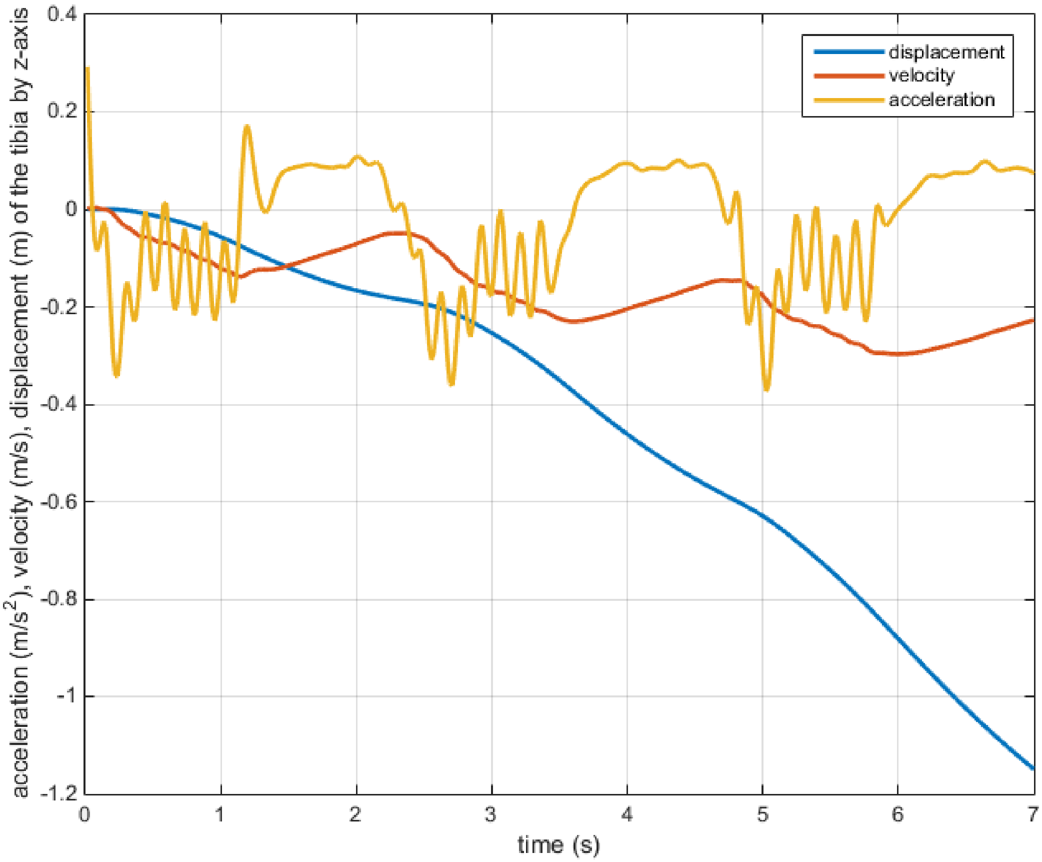


Figure 4.11. Acceleration, velocity and displacement of the point 7(рис 4.9) by Z-axis. Yellow line shows acceleration, red line shows velocity, blue line shows displacement

Because during the motion capture using Vicon system input signal is directly trajectory - the data processing process is simplified substantially.

Processing of the data obtained during the motion capture using Vicon system:

- Export data. The data obtained by the passive optical motion capture systems are exported to the MATLAB.
- Segmentation data. At this step from overall data array selects data which necessary for the analysis. In this research examines the time period equal to 7 seconds.
- Data Visualization. At this stage graph of trajectory of the point was visualized.

Trajectory obtained by passive optical motion capture system, is represented in Figure 4.12.

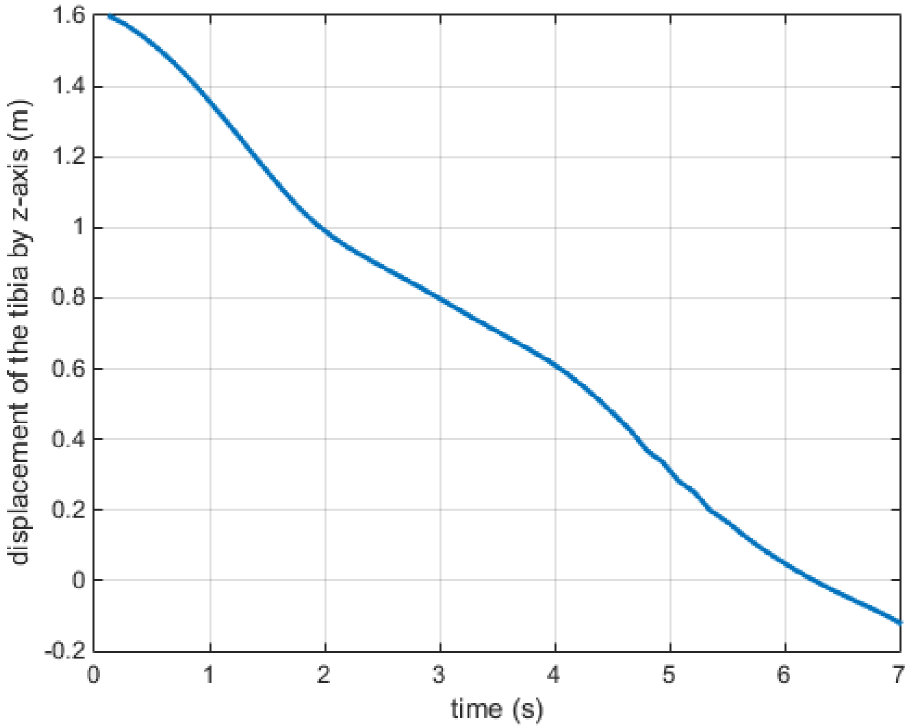
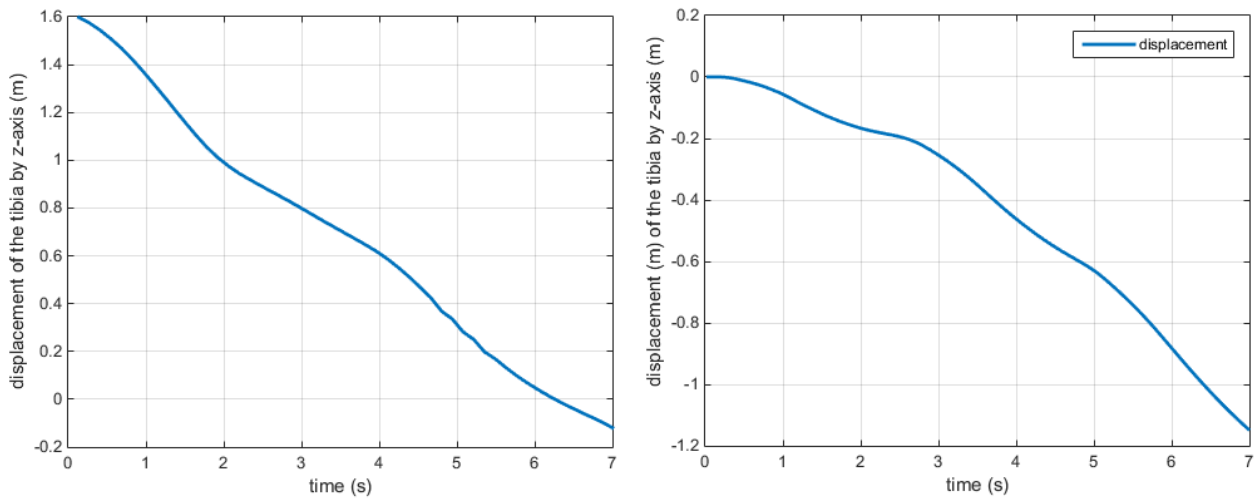


Figure 4.12. Displacement of the point 4 (рис 4.9) by Z-axis.

Based on the data obtained after processing of the original data in the MATLAB comparison of displacements of points 4 and 7 obtained by different methods can be made. This displacements are shown on the figure 4.13. (Difference between this two points are minimal.) The graphs correspond, with some error, the actual displacements during the experiments.



a) b)

Figure 4.13. Displacement comparison. Displacement obtained by optical method (a) Displacement obtained by inertial method (b).

Despite the outward conformity to the real data, in figure 4.11 clearly visible error which occur during integration. This mistake accumulates and makes the data unusable, therefore, using of passive optical motion capture system is preferable, because it requires no integration.

4.5. Conclusion

During the work was carried out a review of methods of motion capture, and the most appropriate methods of capturing motion were chosen: passive optical motion capture system and inertial motion capture system.

Data obtained using this methods are processed in MATLAB.

Comparison of the data obtained by different methods was made: displacement, with some error corresponds to the actual movements. However, data from Vicon system will be used later because during the processing of this data there is no error of integration.

5. MODEL OF THE KNEE JOINT

5.1. Analogues overview

There are many approaches to the modeling of the knee joint, each model is individual and considers the knee joint in accordance with the purposes and objectives of research. Several groups can be distinguished among the knee joint models:

- Models using three-dimension representation of the knee joint elements surfaces. For example, the model "Open the knee", designed for the studying of the knee joint mechanical function, its healthy and damaged tissue structures [31]; model using three-dimensional computer model to predict the total knee motion [32] and the model for estimate and predict the pressure forces generated in the knee joint [33].
- Models that simulate some structures of the knee joint. For example, the model which simulates the behavior of the muscles during movement of the human's knee joint [34], model which proves the importance of ligaments modeling, without losing the properties of the tissues from which ligaments are made up [35], the model which is considering how gait's biomechanics changes after tearing the anterior cruciate ligament[36].
- Models which imitate motion of the knee joint. They can be divided on:
    a) Models which take into account only one degree of freedom of the knee joint. For example spherical mechanism with one degree of freedom for modeling the human knee joint [37].
    b) Models which take into account from two till five degrees of freedom of the knee joint. For example six-membered mechanism which imitate four degrees of knee joint’s freedom [3].
    c) Models which imitate six degrees of freedom of the knee joint. This models usually imitate six degrees of freedom and three-dimension models of the knee joint. This models can be used for determining and explaining the load acting on anterior cruciate ligament during the gait [38] or for checking the effect of an isolated valgus moment on the tension in the anterior cruciate ligament [39].
- Models which imitate knee joint supported by orthosis. For example model which consider knee joint supported by passive orthosis [7].

Despite of all the variety of models simulating the knee joint, during the review analogues neither one model that simulates the movement of the knee joint, supported by an active orthosis was not found therefore the task of creating of this model is relevant.

5.2. Description of created model

The main reason of creating model – simulation movement of the knee joint in sagittal plane.

One of the most important objectives during model creation was to provide anatomically correct trajectories of the tibia and patella. It is caused by the fact that the model was created for testing of the effect of various designs of the active orthoses on the biomechanics of the knee joint. This model can be used in medical applications to simplify the process of selection of the active orthosis for the knee joint.

In its structure, the model simulates a simplified form of the knee joint's elements. Functional task of the model - to move as close as possible to the real movement of the knee joint during walking. Structurally, the model is based on the average data of the bones dimensions and a simplified representation of the mating surfaces of the bone.

Length of links simulating length of bones and other parameters can be changed in accordance with the parameters of particular humans [40-42].

Consider the mechanism which stimulates the movement of the knee joint in the sagittal plane. It's kinematic scheme is shown in Figure 5.1.

At this scheme link 8 represents tibia, link 5 represents femur, this two links simplistically imitate connected surfaces which forming the knee joint. Movement of the link which imitates tibia around link which imitates femur caused by presence of links which simulate cruciate ligament. Cruciate ligament are imitated by links 6 and 7, where link 6 imitates anterior cruciate ligament and link 7 imitates posterior cruciate ligament. Point L of this mechanism is instantaneous center of velocity. Link 4 imitates patella and patella’s ligament, it’s corrected motion is provided by link 3. Links 1 and 2 provide quadriceps and tendon of quadriceps. Changing the total length of these links caused by the translational pair between them leads to the moving of mechanism.

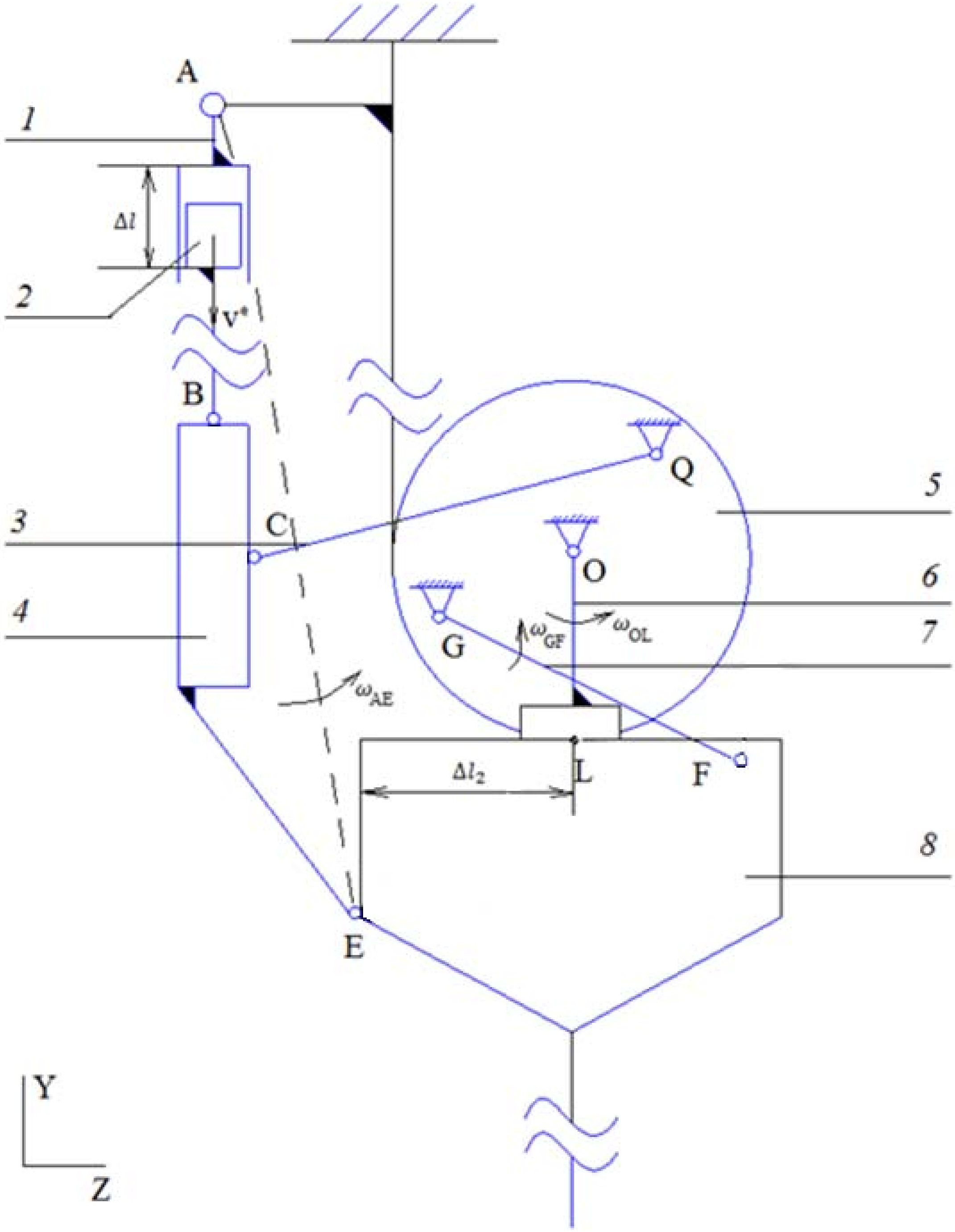


Figure 5.1. Mechanism, which simulates knee joint motion at sagittal plain

It's planar mechanism, it's degree of freedom can be calculated by following equation:

$$w = 3 * (n - 1) - 2P_5 \qquad (5.1)$$

Where:

w – number of degrees-of-freedom

n – number of links, including ground

P_5, – number of the kinematic pairs, which has one degree of freedom

$$w = 3 * (8 - 1) - 2 * 10 = 1 \quad (5.2)$$

Thus, this mechanism has one degree of freedom. Since the research is directed to the simplifying of the rehabilitation period that the simulated knee was injured can be assumed. This allows us to conclude that one degree of freedom for this model is enough because any additional degree of freedom can be re-injure knee joint.

5.3. Kinematic analyze of mechanism

Surfaces of the tibia slide over surfaces of femur. Assumed that surface of femur is two rigidly interconnected spheres (link 5), and surface of tibia is plane (link 8). Static Cartesian's coordinate system was associated with femur. Beginning of the Cartesian's coordinate system (point O) is situated equidistant between two centers of spheres. Axis OX is perpendicular to sagittal plane, axis OZ is directed left, axis OY is directed so that the coordinate system OXYZ is right.

The equation of the surfaces of two rigidly interconnected spheres at OXYZ coordinate system can be written as:

$$(x - a)^2 + y^2 + z^2 = R^2 \quad (5.3)$$

$$(x + a)^2 + y^2 + z^2 = R^2 \quad (5.4)$$

where:

a – distance between beginning of the Cartesian's coordinate system and centers of the spheres,

R – radius of the sphere.

Consider links, which simulate circular ligaments (anterior cruciate ligament – link 6, posterior cruciate ligament – link 7). Links, which simulate circular ligaments impose limitations to links 5 and 8. This limitations can be written as:

$$(Z_F - Z_G)^2 + (Y_F - Y_G)^2 = GF^2 \quad (5.5)$$

$$(Z_L - Z_O)^2 + (Y_L - Y_O)^2 = LO^2 \quad (5.6)$$

$$(Z_F - Z_L)^2 + (Y_F - Y_L)^2 = (LF + \Delta l_2)^2 \quad (5.7)$$

where:

Z_L, Z_O, Z_F, Z_G, Y_G, Y_L, Y_O, Y_F – coordinates points of links attachment,

LO, LF, GF – distance between points L and O, L and F, G and F correspondently,

Δl_2 – displacement of sliding block L along contact plane of the link 8.

In this research patella (link 4) was considered as disk, with radius R1 and thickness (R1=0.75*R), disk rigidly connected with rod, which simulates lower part of patella's ligament, this rod connected with link 2 by flat joint. Also link 4 movably connected with link 3 and link 3 connect with link 5. This links impose some limitations to mechanism, this limitations can be written as:

$$(Z_Q - Z_C)^2 + (Y_Q - Y_C)^2 = QC^2 \tag{5.8}$$

$$(Z_B - Z_C)^2 + (Y_B - Y_C)^2 = BC^2 \tag{5.9}$$

$$(Z_E - Z_C)^2 + (Y_E - Y_C)^2 = EC^2 \tag{5.10}$$

$$(Z_E - Z_B)^2 + (Y_E - Y_B)^2 = EB^2 \tag{5.11}$$

$$(Z_E - Z_F)^2 + (Y_E - Y_F)^2 = EF^2 \tag{5.12}$$

$$(Z_E - Z_L)^2 + (Y_E - Y_L)^2 = \Delta {l_2}^2 + LE^2 + \frac{\Delta l_2 \cdot (LE^2 + LF^2 + EF^2)}{LF} \tag{5.13}$$

where:

Z_L, Z_E, Z_C, Z_Q, Z_B, Z_F, Y_L, Y_E, Y_C, Y_Q, Y_B, Y_F – coordinates points of links attachment,

Q_C, B_C, E_C, E_B, E_F, L_E, L_F – distance between points Q and C, B and C, E and C, E and B, E and F, L and E, L and F correspondently.

Δl_2 – displacement of sliding block L along contact plane of the link 8.

In addition to bones and ligaments, quadriceps (links 1, 2) was modeled too. At this research assumed that quadriceps is extensible. This links also impose some limitations to mechanism, this limitations can be written as:

$$(Z_B - Z_A)^2 + (Y_B - Y_A)^2 = (AB + \Delta l)^2 \tag{5.14}$$

where:

Z_A, Z_B, Y_A, Y_B – coordinates points of links attachment,

AB – distance between points A and B.

Divide the mechanism into two of more simple mechanism for convenience is called them as "upper" and "lower" and consider each separately. Figure 5.2. shows the kinematic system of "upper" mechanism.

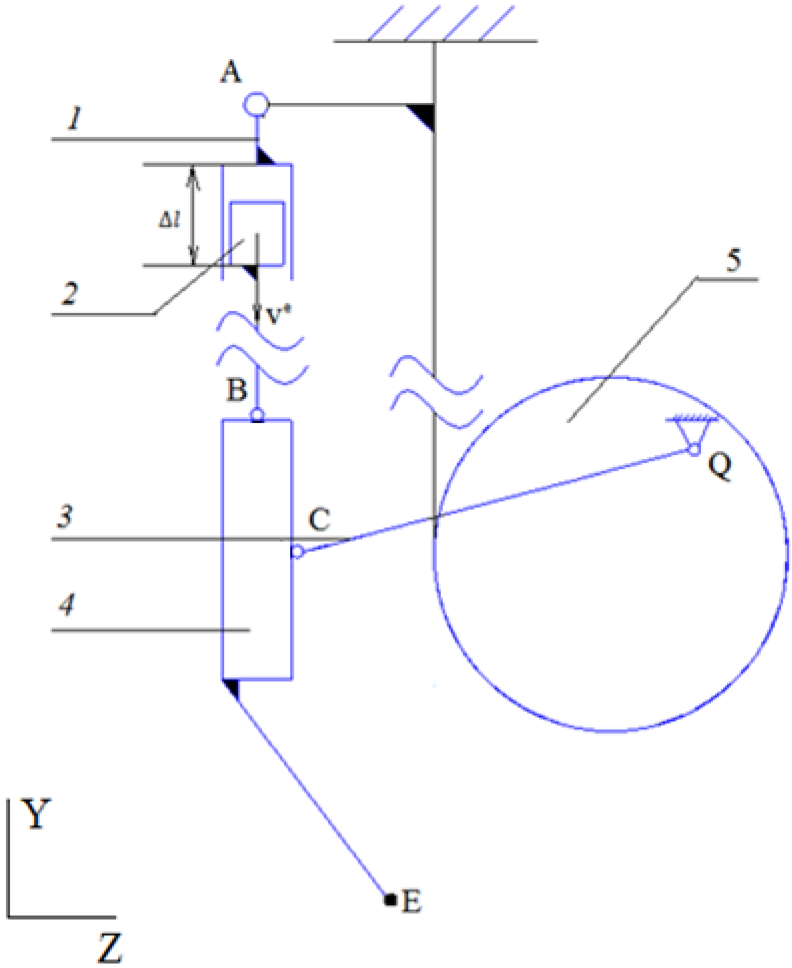


Figure 5.2. Kinematic system of "upper" mechanism.

Number of degrees of freedom can be calculated by equation (5.1):

$$w = 3 * (5 - 1) - 2 * 5 = 2 \quad (5.15)$$

Thus mechanism has two degrees of freedom. However motion of the point E is uniquely determined by the movement of the "lower" mechanism. This mechanism is shown in Figure 5.3.

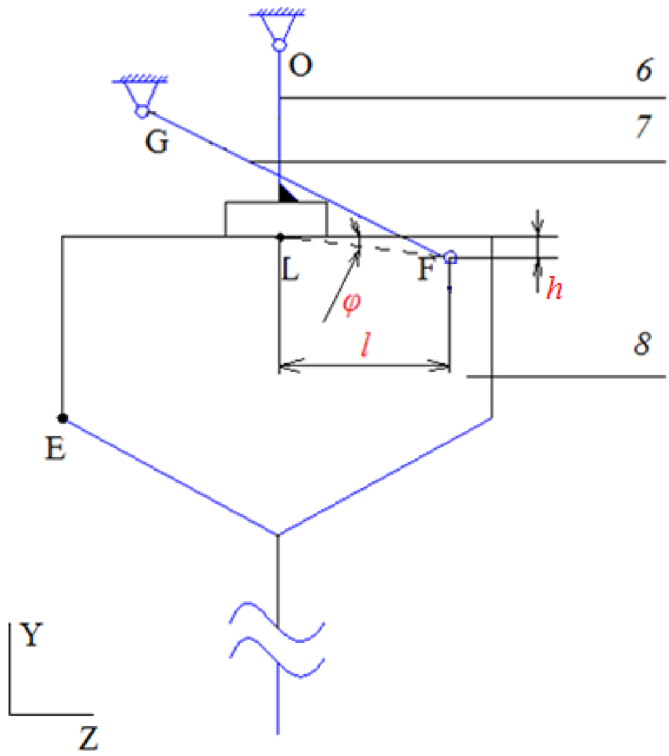


Figure 5.3. Kinematic system of "lower" mechanism.

Number of degrees of freedom can be calculated by equation (5.1):

$$w = 3 * (4 - 1) - 2 * 4 = 1 \quad (5.16)$$

Thus mechanism has one degree of freedom.

In this cases equations which determine motion of the all mechanism can be written as:

$$Z_F = Z_L + l \cdot \cos\varphi + h \cdot \sin\varphi \quad (5.17)$$

$$Y_F = Y_L + l \cdot \sin\varphi + h \cdot \cos\varphi \quad (5.18)$$

$$Z_L = Z_O + OL \cdot cos\,\varphi \quad (5.19)$$

$$Y_L = Y_O + OL \cdot sin\,\varphi \quad (5.20)$$

$$(Z_F - Z_G)^2 + (Y_F - Y_G)^2 = GF^2 \quad (5.21)$$

Add equations (5.19), (5.20) at equations (5.17) и (5.18), and than add found equations at the equation (5.21) result can be written as:

$$(Z_O + OL \cdot cos\,\varphi + l \cdot \cos\varphi + h \cdot \sin\varphi - Z_G)^2 + \\ +(Y_O + OL \cdot sin\,\varphi + l \cdot \sin\varphi + h \cdot \cos\varphi - Y_G)^2 = GF^2 \quad (5.22)$$

where:

$Z_F,\ Y_F,\ Z_L,\ Y_L,\ Z_O, Y_O,\ Z_G, Y_G$ – coordinates points of links attachment,

OL и GF – distance between points O and L, G and F correspondently,

φ – angle between the line segment LF and the plane which simulates surface of the tibia,

l – length between L и F, projection on Z-axis,

h – length between L и F, projection on Y-axis.

Equation (5.22) - the law of movement of the mechanism, expressed in an implicit form. Motion determined by link 2, then classically Lagrange equation was written. From this equation all necessary kinematics characteristics can be found. For a given mechanism law of motion in an explicit form can not be written, and therefore velocity of links, in explicit form, can not be recorded also. Lagrange equation of dynamics also can’t be written in explicit form, because it requires speed links derived explicitly. However, this problem can be solved numerically.

5.4. Conclusion

Despite of all the variety of models simulating the knee joint, during the review analogues neither one model that simulates the movement of the knee joint, supported by an active orthosis was not found therefore the task of creating of this model is relevant.

During the work mechanism for simulating the knee joint was created , this mechanism is flexible enough, personalizing the model .

Designed mechanism was analyzed from point of kinematics. Lagrange equation of dynamics for this mechanism can not be derived in an explicit form, however, this problem can be solved numerically.

6. CREATION MODEL IN MATLAB

6.1. Software MATLAB

6.1.1. MATLAB Simulink

MATLAB (short for English «Matrix Laboratory».) - A software package for solving technical tasks and eponymous programming language used in this package.

MATLAB Simulink - graphical environment for simulation modeling, dynamic models in Simulink are constructed as directed graphs, using block diagrams. Simulink includes libraries for simulation of electric power, mechanical and hydraulic systems. Complete blocks, broken by libraries allows quickly and efficiently create models.

After creating of the model simulation of dynamic properties of model can be performed. Simulation results can be viewed in real-time. To ensure the required speed of the simulation in Simulink has built-solvers, with fixed or variable pitch.

Simulink software allows to generate a plurality of different signals, for systems management, for example, a constant signal, a sine wave, a pulse sequence, random effects with a uniform distribution law, "white noise" type signal for continuous systems, a step function, etc. Also created models can be controlled by using the built-in blocs of management systems that are configured for specific tasks.

For creation of the model of the knee joint SimMechanics library was used. This library is designed to simulate the mechanical motion of solids. SimMechanics software package can solve the spatial problems of statics, kinematics and dynamics of mechanical multilink objects. The main difference between the model created in SimMechanics is that the mechanism is modeled directly instead of mathematical modeling data of mechanisms movement.

Not less important option of the SimMechanics package are tools of visual observation, they can start 3D animation of system during the modeling process. In addition SimMechanics package allows download 3D models of system's elements for a visual animation [43].

6.1.2. Model Predictive Control Toolbox

Model Predictive Control Toolbox - is a package that allows to explore and to design control algorithms with the prediction of dynamics. It is used for solve practical control problems of complex processes with one or more I / O in the presence of a large number of limitations.

The package allows to implement principle of control wherein based on an internal model of the object, input action is calculated at each step. Programming optimization is performed using quadratic programming.

The main advantage of MPC-approach, by which it has been successfully used in the construction and operation of control systems - the relative simplicity of the basic scheme of the formation of feedback, combined with high adaptive properties. High adaptive properties provide control of multi-dimensional and multiply connected objects with a complex structure, includes non-linearity, allow to optimize processes in real time within the limitations on the control and controlled variables, in addition, allow to take into account the uncertainty in the determining of objects and disturbances [44].

Knee joint model controlled by the package Model Predictive Control Toolbox. It allows dynamic management on the basis of the numerical method.

6.2. Creation of the healthy knee joint model

For modeling of the knee joint movement, supported by orthoses, it is necessary to create a model which simulates the movement of a healthy knee. The model which simulates the movement of a healthy knee joint is shown in Figure 6.1.

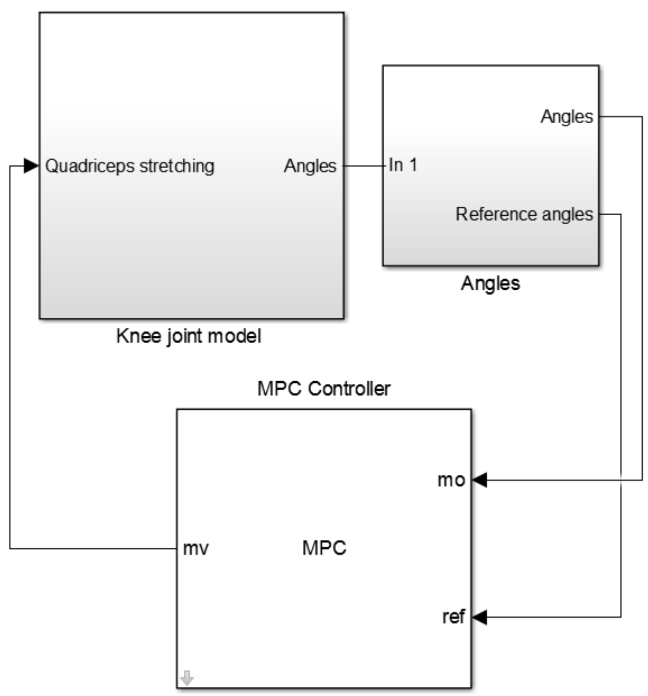


Figure 6.1. Model, which imitates motion of the healthy knee joint

Mathematical calculations of dynamics are automated and performed using MPC block which is part of MATLAB / Simulink. MPC Controller allows to control stretching of the quadriceps (movement in translational pair between links 1 and 2) using the angle between the femur and the tibia in a given time, and the reference values of the angles between the femur and the tibia.

Knee joint model - the most important block of model, which describes a mechanism that simulates a healthy knee joint, is shown in Figure 6.2.

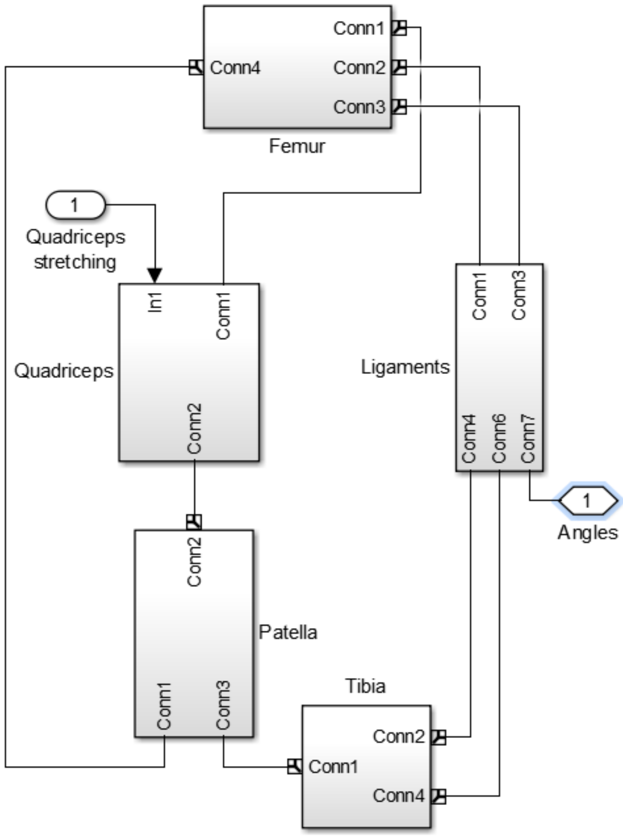


Figure 6.2. Block “Knee joint model”.

For modeling it is necessary to know the model parameters: weight, length of links, moments of inertia and the mutual arrangement of links. All of these parameters are given in model subsystems, each subsystem simulates a certain part of the knee joint.

Femur subsystem simulates the femur, the length of which is equal to 0.46 m, and the radius of the condyles which is 0.03 m. Femur subsystem is shown in Figure 6.3. Also, in this model, subsystem femur serves as the mechanism's ground. The weight of this subsystem should be considered in the sum of the weight of Quadriceps subsystem, since together they constitute the total mass of human’s hip. Within the model, the weight of the thigh is 8 kg.

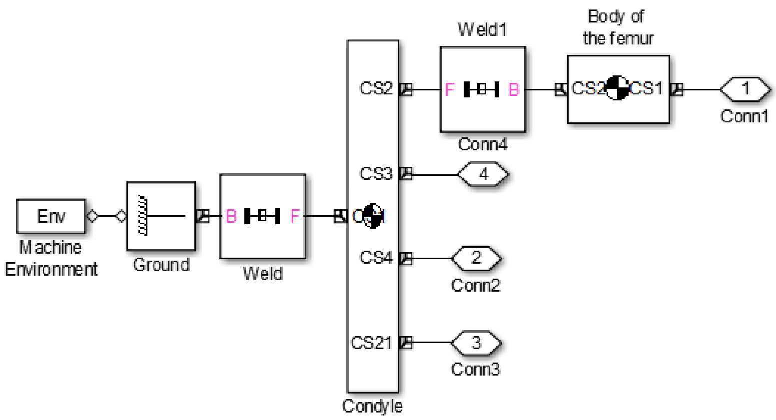


Figure 6.3. Femur subsystem.

Quadriceps subsystem includes link which imitates the quadriceps, link simulating a tendon of quadriceps and link specifying the distance between quadriceps and femur. Motion control of the knee joint model made by using this subsystem. Quadriceps subsystem is shown in Figure 6.4.

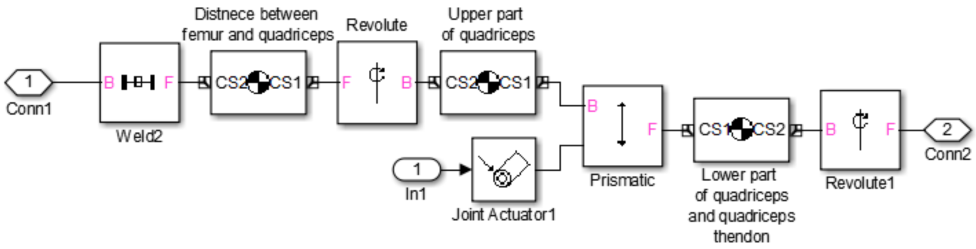


Figure 6.4. Subsystem Quadriceps.

Patella subsystem includes link simulating the patella, patellar ligament and a link that provides the correct movement of the patella, in the framework of this model. Weight of ligaments and tendons is depreciatingly small in this model in relation to other structures of the knee, despite this total weight of the patella and ligament of patella is 0.31kg. The radius of the patella, in the framework of the model is 0.023 m. Patella subsystem is shown in Figure 6.5.

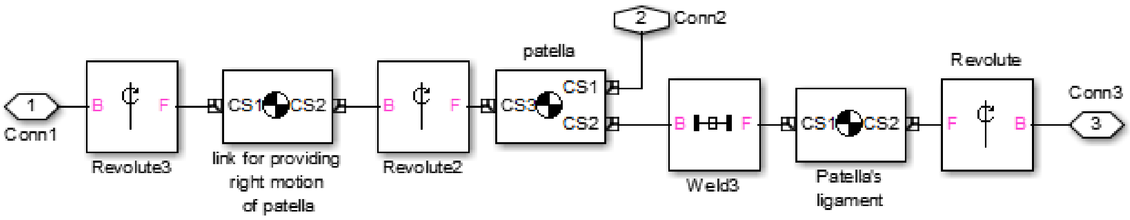


Figure 6.5. Subsystem Patella.

Tibia subsystem simulates the tibia, whose length is 0.4 m, weight of the tibia, in the framework of the model is 3.75 kg. On the basis of the angle between the tibia and the femur, and depending from performing movements (flexion / extension) control of a model of the knee joint is exercised. Tibia subsystem is shown in Figure 6.6.

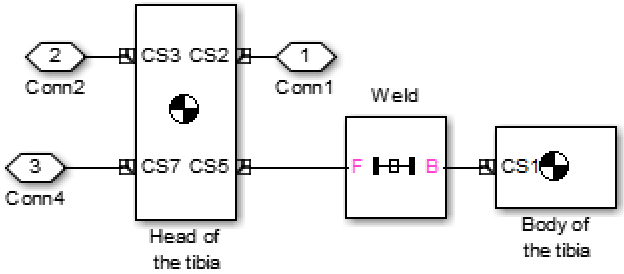


Figure 6.6. Tibia subsystem.

Ligaments subsystem imitates anterior and posterior cruciate ligament. Ligaments acceptance not extensible, however, in this research, due to movement of link, simulating the anterior cruciate ligament, movement along the plane of the tibia is possible. In addition, the movement of these two links defines the total law of the system motion. Ligaments subsystem is shown in Figure 6.7.

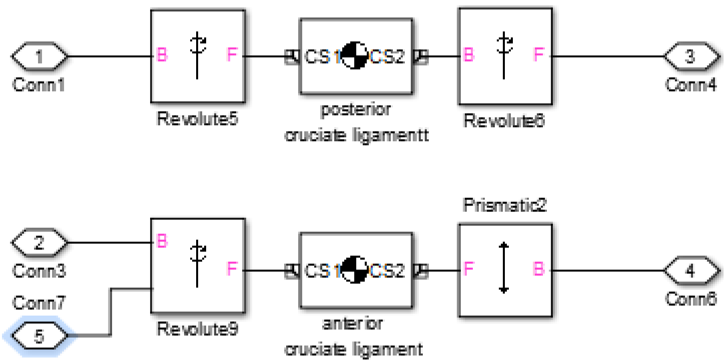


Figure 6.7. Ligaments subsystem.

6.3. Model of orthosis

During the work has been used a model of active orthosis for the knee joint, developed by Nikita Turchinovich, during work on the thesis «Design of knee joint support system». During designing it was decided to orient on the real structure of the knee. The design imitates the work that quadriceps muscle makes during extension of the limb. The torque is transmitted from the motor’s shaft (1) via a toothed - belt transmission (2) to the ball-screw transmission (BST) (3), which, in turn, converts the rotation of the screw into linear motion of quad rods (4). Rods are moving in sliding prismatic joint along the guide (5) and connected via a flat rotary joint with the element conditionally named "patella" (6), which, moving by a difficult trajectory, bends / extends the lower half of the orthosis. The prototype design is shown on Figure 6.8.

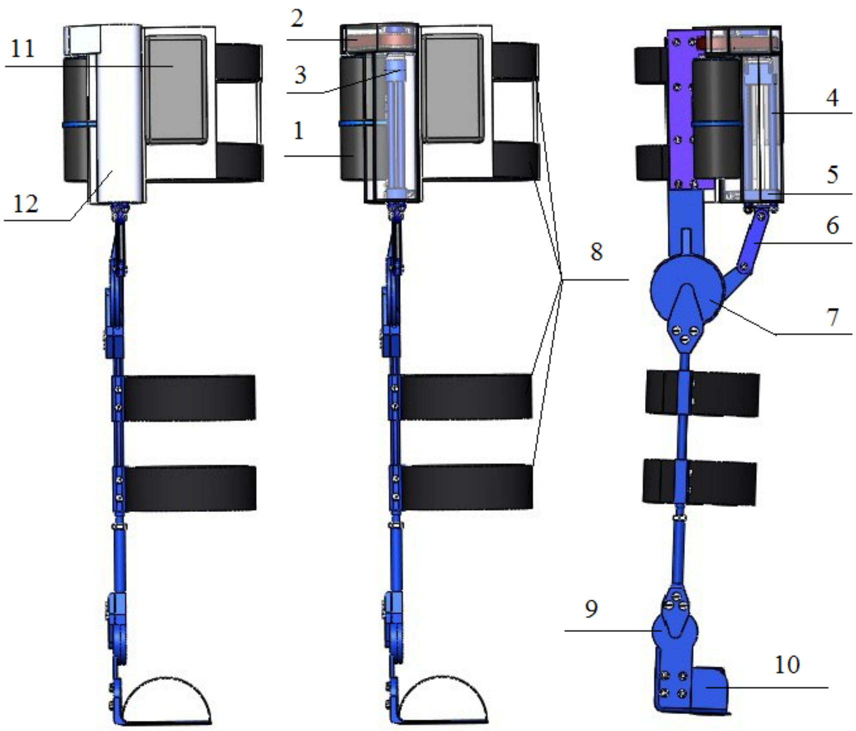


Figure 6.8. The prototype design. a) with protective casing, b) without protective casing.

Where:

1. Engine
2. Toothed - belt transmission.
3. Ball-screw transmission.
4. Rods.
5. Prismatic joint.
6. «Patella».
7. Flat «knee» joint.
8. Fixing belts.
9. Flat «ankle» joint.
10. «Heel-support».
11. Controlling module.

12. Protective casing.

6.4. Model of the knee joint supported by orthosis in MATLAB

For creating knee joint supported by active orthosis, in addition to the knee joint model it is necessary to create a model of active orthosis. As well as for the creation model of the healthy knee joint for creating active orthosis model uses a software MATLAB, it's graphical environment Simulink and SimMechanics library.

Supposed that the knee joint has been damaged, and now is at the stage of rehabilitation, and therefore can not move independently. Remove the control of model of a healthy knee joint, at the same time add to the model of a healthy knee joint model of active orthosis. Orthosis used in the model provides one degree of freedom. In the orthosis model takes into account the offset resulting from displacement of soft tissue [38]. The model simulates the movement of knee joint, supported by active orthosis, is shown in Figure 6.9.

The model imitates movement during the gait and controlled by MPC, however in model supported by orthosis, instead of directly control of knee joint movement, controlled movement of the orthosis, which in their turn provides the necessary movement of the knee.

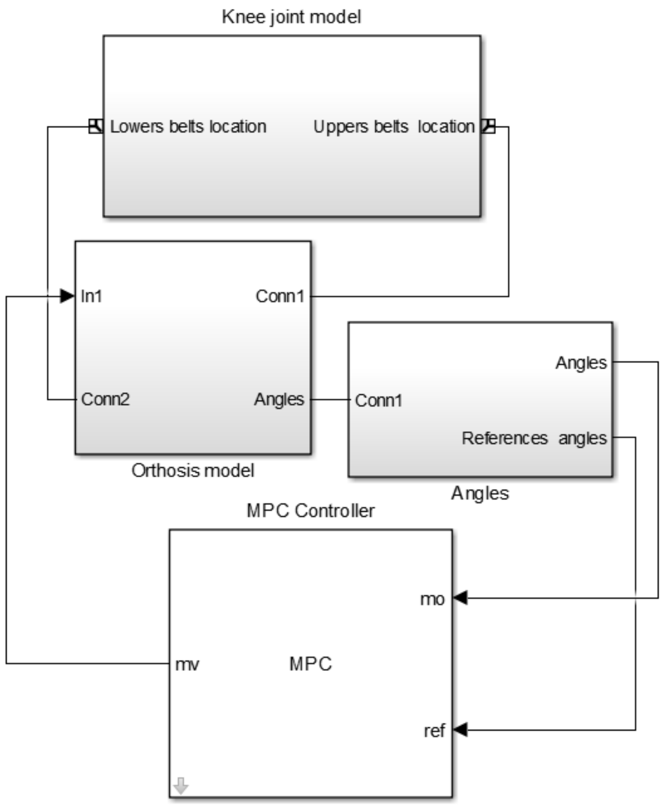


Figure 6.9. Model which imitate motion of the knee joint supported by orthosis.

Subsystem Orthosis model, includes all the key aspects of the of the orthosis structure, such as fixing belts, ball screw pair rods in the guide, "Patella" Planar "knee" joint. Using the MPC controller angle between the upper and lower rails is controlled, and the movement is performed by changing the ball-screw transmission length. The total weight of the orthosis, in the framework of this system is 5.5 kg, including the battery. Subsystem Orthosis model is presented in Figure 6.10.

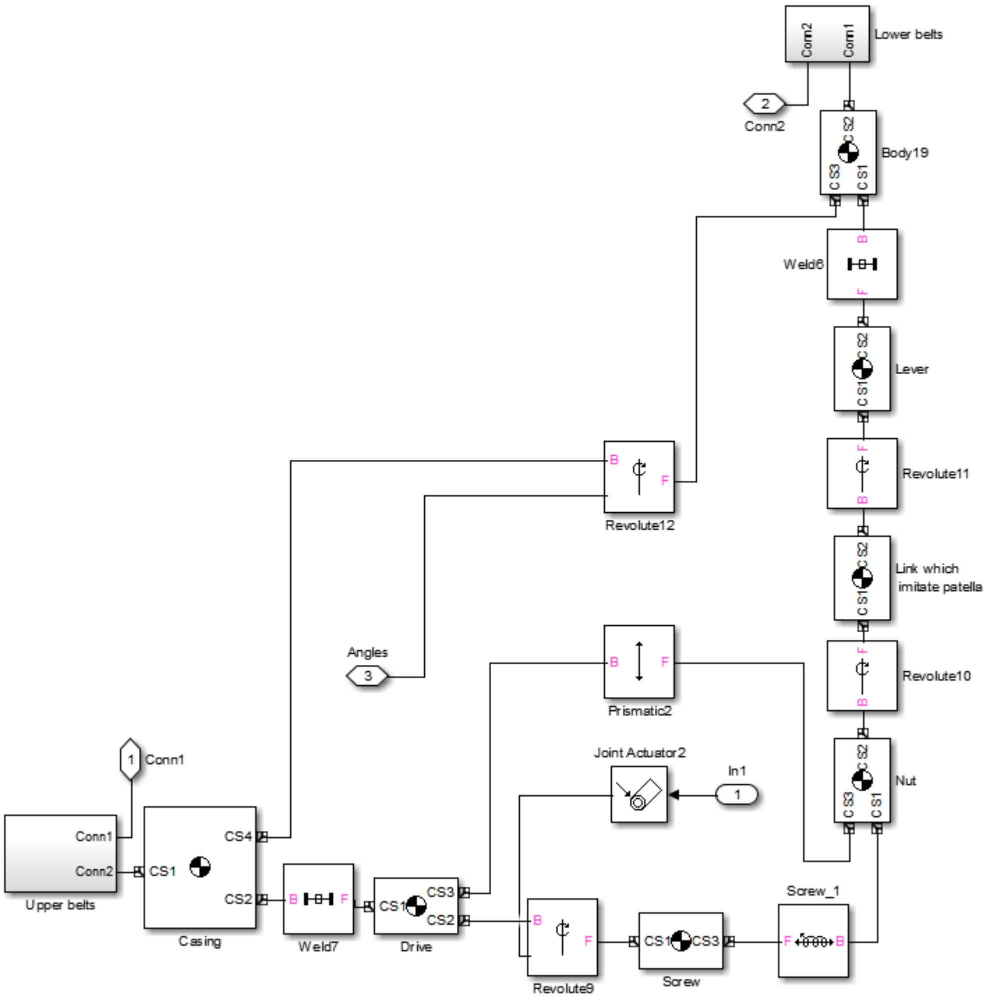


Figure 6.10. Subsistem Orthosis model

6.5. Visualization of the models in MATLAB

For greater clarity, the decision to visualize the model was made. MATLAB allows to build a model, visualized by means of mathematical functions, and add in a ready model 3D models of objects. In this study, the model was visualized using an additional computer graphics.

For visualization block in MATLAB, it is necessary to choose the model and download it in the appropriate block. This operation is performed in the Visualization tab, also in the same tab, it was selected a future color of model and the point with respect to which model is attached. Example of block visualization is shown in Figure 6.11.

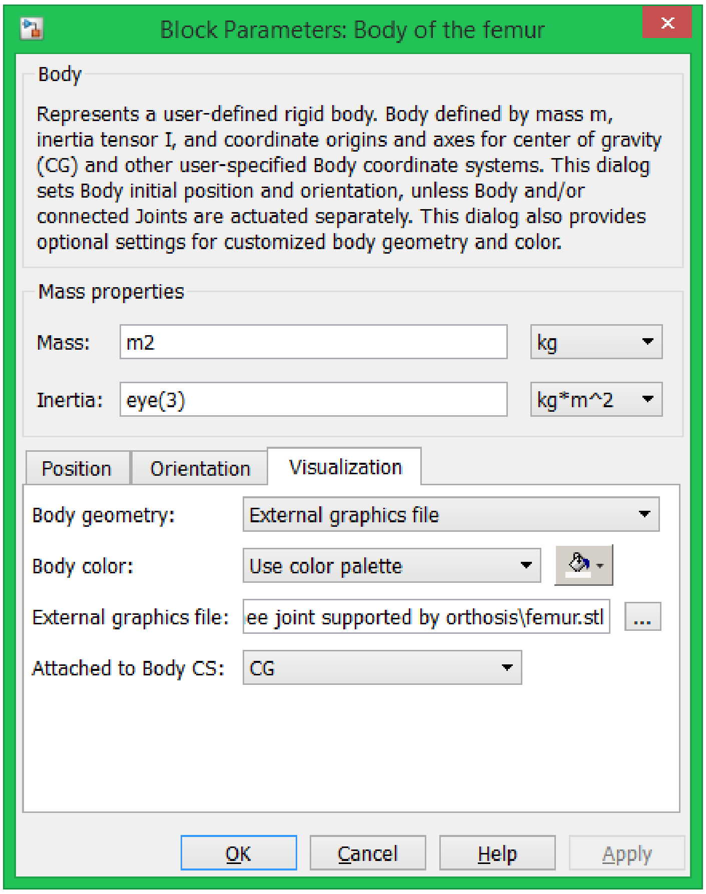


Figure 6.11. Visualization of block in MATLAB

In the model which imitating movement of a healthy knee joint were used model of the femur, tibia and patella exported from ZBrush software. Visualized model which imitating movement of knee joint is shown in Figure 6.12.

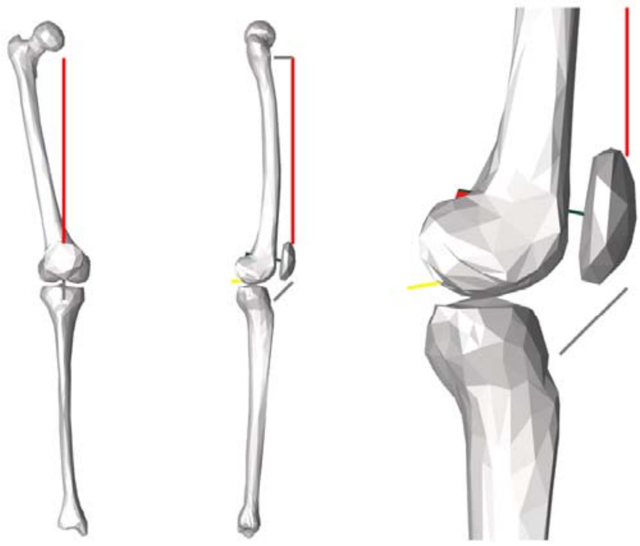


Figure 6.12. Visualized model which imitating movement of the healthy knee joint

In the model which is imitating movement of knee joint, supported by orthosis, in addition to models of the femur, tibia and patella exported from ZBrush software orthosis parts exported from SolidWorks were used. Visualized model which imitating movement of knee joint, supported by orthosis is shown in Figure 6.13.

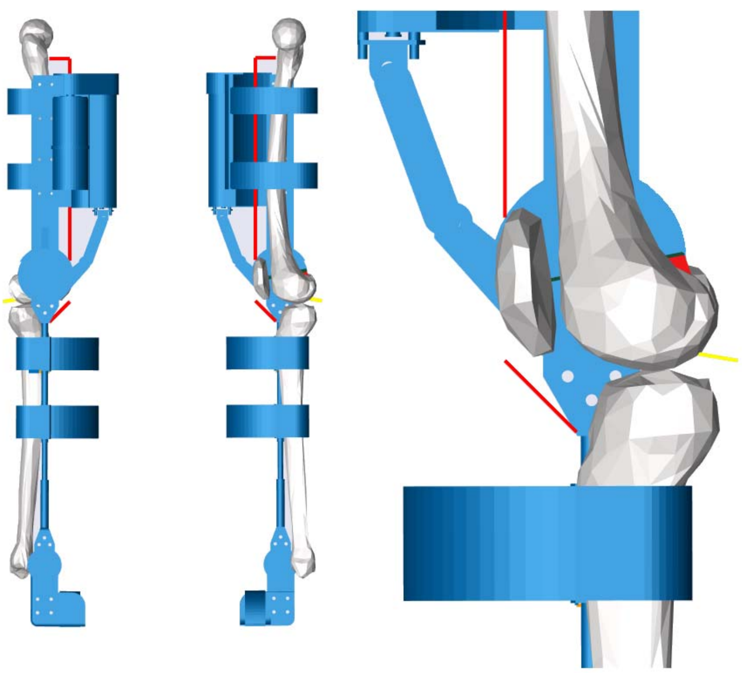


Figure 6.13. Visualized model which imitating movement of knee joint, supported by orthosis.

6.6. Conclusion

To simulate movement of knee joint, supported by orthosis it is necessary to model separately healthy knee joint, and orthosis for a knee joint. And then combine them into a single model.

Model of the knee joint, created in the MATLAB software is flexible and easily adapts to the individual parameters of the person. Parameters of the orthosis model can also be easily changed. In the knee joint model, supported by orthosis taken into account displacement of the soft tissue that occur during movement.

For better visualization the model was visualized. During visualization, it were used models exported from ZBrush software , and SolidWorks.

7. SIMULATION RESULTS

7.1. Operating modes of the models

For created system, there are two modes: simulation and animation during simulation.

Model work in simulation mode. To simulate the model it is necessary to run the program with a resolution '.m'. Block diagram of the program is shown in Figure 7.1.

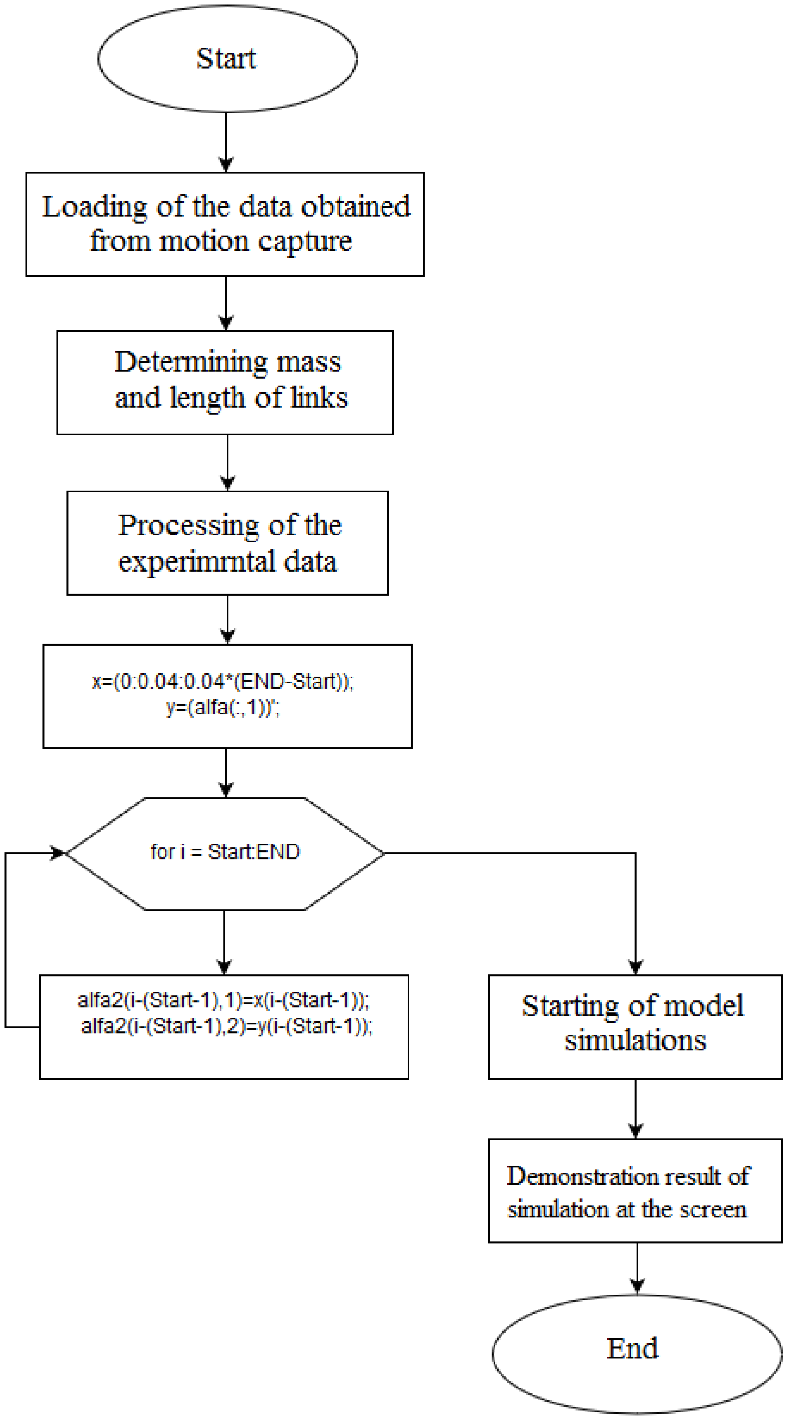


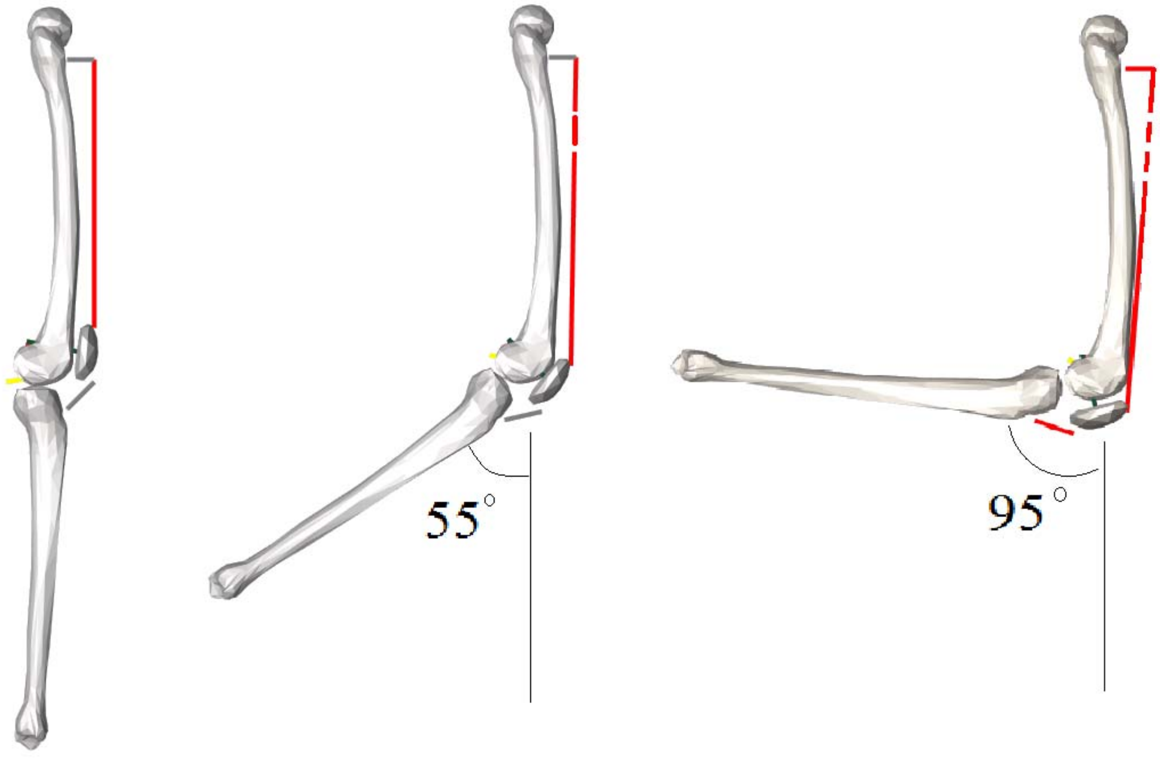
Figure 7.1. Block diagram of the program that provides working model without visualization.

After finishing the program comparison of the simulation results and data obtained during the motion capture will be displayed as graphs.

Working of model in animation mode during the simulation. In this case, it is necessary run the file with a resolution of '.slx', and then, without running the model, run the program with a resolution '.m' ,. After that, during a simulation of the program movement of three-dimensional model will be displayed, wherein after end of the program comparison of the simulation results and data obtained during the motion capture will be displayed as graphs.

7.2. Results of working model which simulated motion of the healthy knee joint

Results of working model which simulated motion of the healthy knee joint is represented on the figure 7.2.



a) b) c)

Figure 7.2. Model which imitates healthy knee joint. a) starting position, b) maximal angle of flexion during the gait, c) flexion of the knee joint

Results of simulation comparison with data obtained using motion capture system Vicon. Comparison is shown on the figure 7.3.

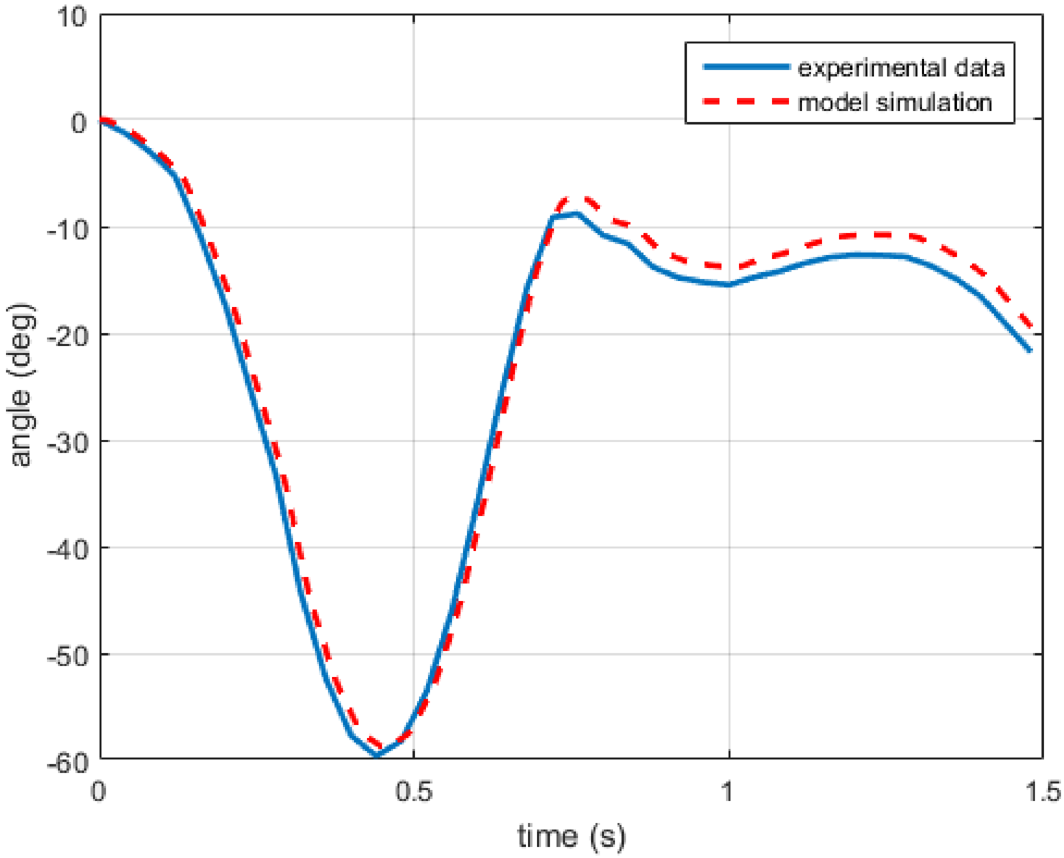
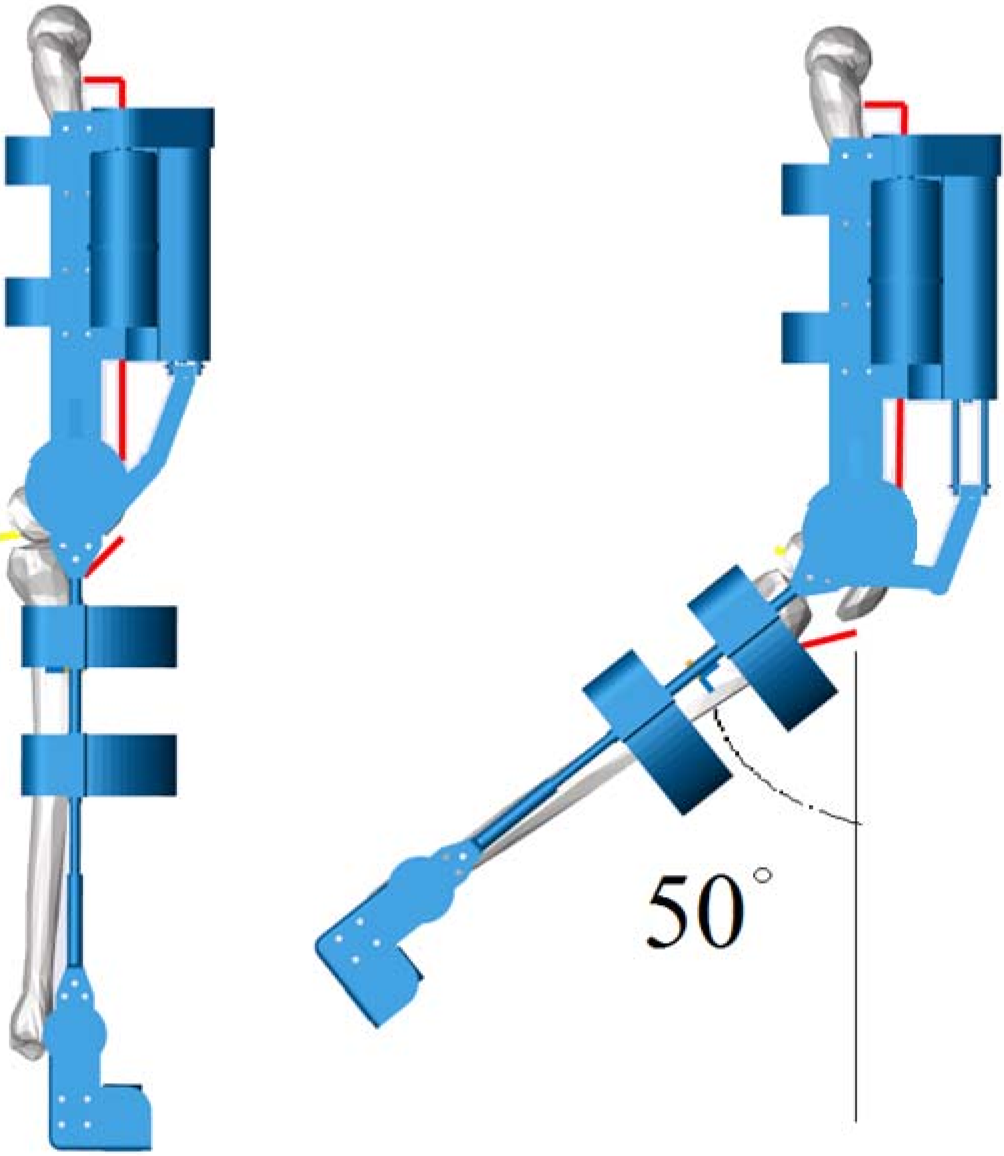


Figure 7.3. Comparison results of models work, which simulate healthy knee joint (red line) and data, obtained from motion capture system (blue line)

Blue solid line shows changing of angle between tibia and femur dependency from time during real gait, red dashed line represents variation of the angle between tibia and femur during the simulation.

7.3. Results of the working model which imitate motion of the knee joint supported by orthosis

Result of the working model which imitate motion of the knee joint supported by orthosis is represented on the figure 7.4.



a) b)

Figure 7.4. Model which imitates motion of the knee joint supported by orthosis a) start position, b) maximal angle of flexion during the gait.

Results of models work, which simulate knee joint supported by orthosis, also were compared with data of real human gait obtained from motion capture system (Vicon). Comparison is represented on the figure 7.5.

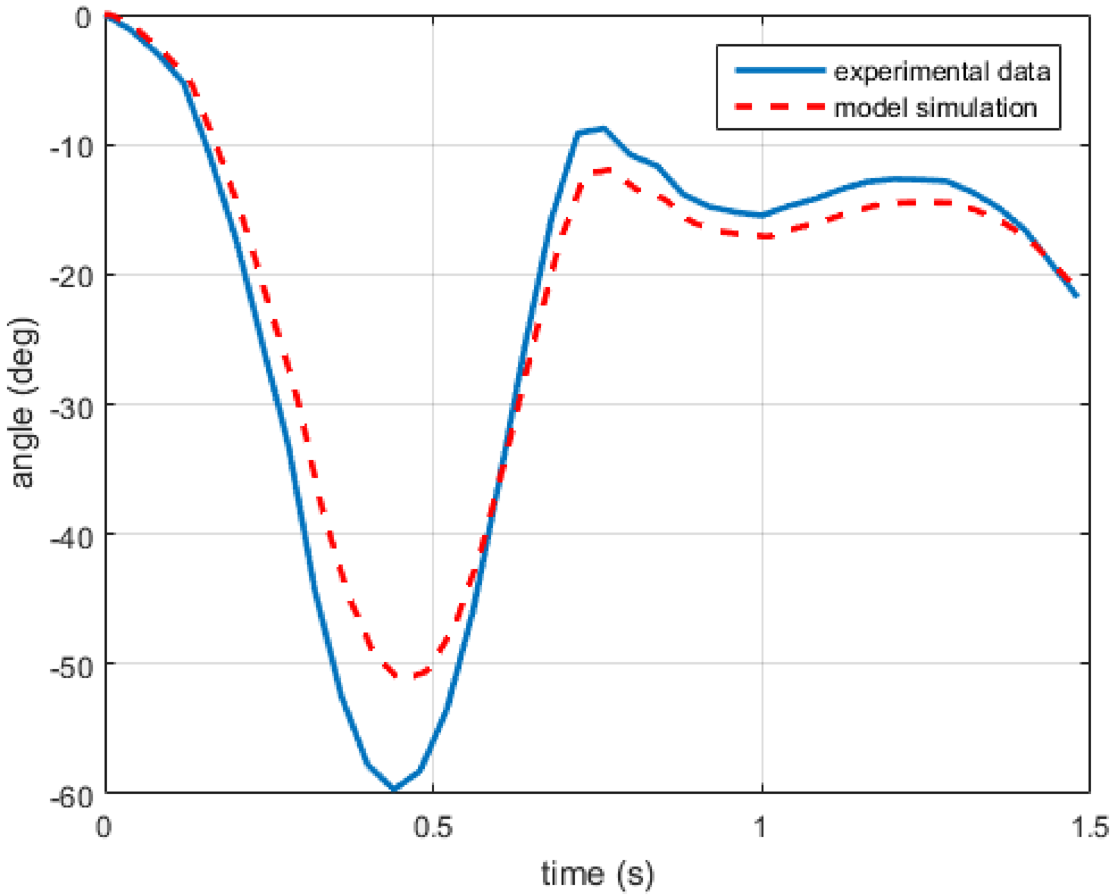


Figure. 7.5. Comparison results of models work, which simulates knee joint, supported by orthosis (line 1) and data, obtained from motion capture system (line 2)

Blue solid line shows changing of angle between tibia and femur dependency from time during real gait, red dashed line represents variation of the angle between tibia and femur during the simulation.

7.4. Conclusion

Created model can be run in simulation mode, and in animation during simulation mode. Regardless of the mode after the end of the simulation of the model graphs that compare the data obtained during simulation with the data obtained using the motion capture are displayed.

Based on analysis of simulation result, conclusion that general dynamics of movement of the received model corresponds to movements of the real knee joint was made, however in the case of the knee joint model, supported by orthosis clearly visible the limitations of orthosis .

SUMMARY

The knee joint is one of the most complex joints in the human locomotor apparatus. Because of the complexity of the knee joint during the simulation has to resort to simplifications that have an impact on the accuracy of the research resulting data.

Analysis of the most common injuries showed that the knee injuries are dangerous by themselves, and during the rehabilitation period. During the rehabilitation period passive and active orthoses used often, but the selection and fitting of orthoses long and laborious process, therefore place of fixing, type and design of the orthosis should have a significant impact on the model of the knee joint, supported by orthosis.

Since the trajectory the knee joint elements, largely determined by the presence of soft structures such as ligaments and muscle they must be imitated in the model the knee joint.

For reference data for checking model, data obtained during Vicon motion capturing opposed to the data obtained by the inertial method, were selected, since they are deprived of the integration errors.

Despite of all the variety of models simulating the knee joint, during the review analogues neither one model that simulates the movement of the knee joint, supported by an active orthosis was not found therefore the task of creating of this model is relevant. This model can be used in medical applications to simplify the process of selection of the active orthosis for the knee joint.

Mechanism that simulates movement of the knee joint in sagittal plane and has one degree of freedom was created. Since research aimed at facilitating rehabilitation period, it can be assumed that the simulated knee was injured. It enables us to conclude that one degree of freedom for this model is enough because any additional degree of freedom can be re-injure knee joint

Designed mechanism which imitate knee joint was analyzed from points of kinematics.

Model of the healthy knee joint and model of the knee joint supported by orthosis were created in MATLAB software. Models created in such manner that it was possible to change the parameters of knee joint, depending on the individual characteristics of the patient's knee joint. To increase the clarity, the models was visualized.

Based on analysis of simulation result, conclusion that general dynamics of movement of the received model corresponds to movements of the real knee joint, however in the case of the knee joint model, supported by orthosis clearly visible the limitations of orthosis .

During further research planned to improve model in the direction of increasing of anatomic: addition knee joint model elements that are not represented during of this work, such as hyaline cartilage, menisci, collateral ligaments, hamstrings. Additionally analysis of the model from point contact stresses is planned.

KOKKUVÕTE

Põlveliiges on üks keerulisemaid liigeseid inimese tugiliikumisaparaadis. Selle tõttu põlveliigese liikumise simuleerimisel tuleb teha lihtsustusi, mis omakorda avaldab mõju uurimistulemuste täpsusele.

Enamlevinud põlveliigese vigastuste analüüsist selgus, et tuleb hoolikalt jälgida kindlat raviskeemi ja omada infot liigese seisundi kohta rehabilitatsiooni perioodi jooksul. Selleks kasutatakse aktiivseid ja passiivseid ortoose. Ortoosi valik ja selle parajaks tegemine on pikaaegne ja töömahukas protsess, mistõttu ortoosi kinnituskoht, tüüp ja kuju avaldavad olulist mõju ortoosiga toestatud põlveliigese mudelile.

Põlveliigese mudeli koostamisel tuleks arvesse võtta, et põlveliigese liikumise trjektoor on enamasti määratud pehmekudede liikumisega.

Etalonandmeteks mudeli töö kontrollimiseks olid valitud andmed, mis olid saadud süsteemi Vicon abil, kuna erinevalt inertsimeetodi abil saadud tulemustest need ei sisalda integreerimisviga.

Vaatamata põlveliigese liikumist simuleerivate mudelite rohkusele, pole leitud ühtegi analoogi, kus oleks pakutud ortoosiga toestatud põlveliigese liikumise simulatsioon. Selle magistritöö eesmärgiks ongi koostada ortoosiga toestatud põlveliigese liikumise simulatsioon. Simuleerimise tulemusena saadud mudelit võib rakendada meditsiinis lihtsustamaks ortoosi valiku ja sobitamise protsessi.

Põlveliigese liikumist simuleerival mehhanismil on üks liikumise vabadusaste. Kuna uurimistöö tulemused on plaanis rakendada rehabilitatsiooni perioodi jooksul, siis võib eeldada, et simuleeritakse vigastatud põlve liikumist. Järelikult ühest vabadusastmest peaks piisama, sest kui anda põlveliigesele lisa liikumise vabadustastemid, siis see võib põhjustada liigese lisavigastusi.

Töös oli teostatud põlveliigest imiteeriva mehhanismi kinemaatika analüüs.

Terve põlveliigese ja ortoosiga toestatud põlveliigese mudel olid koostatud kasutades MATLAB tarkvara. Mudelid oli koostatud selliselt, et oleks võimalik muuta põlveliigese parameetreid, kohendades neid ja võttes arvesse teatud patsiendi põlveliigese karakteristikuid. Mudelid olid visualiseeritud, et simuleerimise protsessi näitlikkustada.

Tuginedes simulatsiooni tulemuste analüüsile, võib teha järelduse, et modelleeritud liigese liikumise üldine dünaamika vastab reaalse põlveliigese liikumise dünaamikale väljaarvates ortoosi mõju, mis takistab teatud tüüpi liikumisi.

Tulevikus plaanitakse saadud mudelit edasi arendada, lisades sellele anatoomilist täpsust. Lisaks, tuleks teostada mudelis esinevate kontaktpingete analüüs.

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APPENDICES

Text of the program for simulating motion of the knee joint supported by orthosis (healthy knee joint) model

```
%% Cleaning of the memory
clc;
clear;
% Loading data from motion capture system
load ('data.mat')
 % Determining of link's lengths
l1=400/1000;
R=30/1000;
l2=340/1000;
l3=175/1000;
l4=77/1000;
l5=83/1000;
l6=120/1000;
l7=149/1000;
l8=60/1000;
l9=69/1000;
l10=25/1000;
 % Determining of link's mass
m1=1;
m2=4.5;
m3=0.5;
m4=0.05;
m5=0.3;
m6=1.75;
m7=2;
% Experimrntal's data processing
Start=97;
END=133;
for i = Start:END
RTOE(i-(Start-1),1)=Data(i,86*3-2);
```

```
RTOE(i-(Start-1),2)=Data(i,86*3-1);
RTOE(i-(Start-1),3)=Data(i,86*3);
LTOE(i-(Start-1),1)=Data(i,77*3-2);
LTOE(i-(Start-1),2)=Data(i,77*3-1);
LTOE(i-(Start-1),3)=Data(i,77*3);
HIP(i-(Start-1),1)=Data(i,11*3-2);
HIP(i-(Start-1),2)=Data(i,11*3-1);
RKNE(i-(Start-1),1)=Data(i,86*3-2);
RKNE(i-(Start-1),2)=Data(i,86*3-1);
LKNE(i-(Start-1),1)=Data(i,77*3-2);
LKNE(i-(Start-1),2)=Data(i,77*3-1);
RTOE2(i-(Start-1),1)=Data(i,93*3-2);
RTOE2(i-(Start-1),2)=Data(i,93*3-1);
RANK(i-(Start-1),1)=Data(i,89*3-2);
RANK(i-(Start-1),2)=Data(i,89*3-1);
RHEL(i-(Start-1),1)=Data(i,90*3-2);
RHEL(i-(Start-1),2)=Data(i,90*3-1);
RHIP(i-(Start-1),1)=Data(i,85*3-2);
RHIP(i-(Start-1),2)=Data(i,85*3-1);
LHIP(i-(Start-1),1)=Data(i,76*3-2);
LHIP(i-(Start-1),2)=Data(i,76*3-1);
LTOE2(i-(Start-1),1)=Data(i,84*3-2);
LTOE2(i-(Start-1),2)=Data(i,84*3-1);
LANK(i-(Start-1),1)=Data(i,80*3-2);
LANK(i-(Start-1),2)=Data(i,80*3-1);
LHEL(i-(Start-1),1)=Data(i,81*3-2);
LHEL(i-(Start-1),2)=Data(i,81*3-1);
SPINE1(i-(Start-1),1)=Data(i,23*3-2);
SPINE1(i-(Start-1),2)=Data(i,23*3-1);

a(i-(Start-1),1)=sqrt((HIP(i-(Start-1),1)-RKNE(i-(Start-1),1))^2+(HIP(i-(Start-1),2)-RKNE(i-(Start-1),2))^2);
b(i-(Start-1),1)=sqrt((RANK(i-(Start-1),1)-RKNE(i-(Start-1),1))^2+(RANK(i-(Start-1),2)-RKNE(i-(Start-1),2))^2);
```

```
c(i-(Start-1),1)=sqrt((HIP(i-(Start-1),1)-RANK(i-(Start-1),1))^2+(HIP(i-(Start-1),2)-RANK(i-(Start-1),2))^2);
alfa(i-(Start-1),1)=acos((a(i-(Start-1),1)^2+b(i-(Start-1),1)^2-c(i-(Start-1),1)^2)/(2*a(i-(Start-1),1)*b(i-(Start-1),1)))*180/pi;
a(i-(Start-1),2)=sqrt((HIP(i-(Start-1),1)-LKNE(i-(Start-1),1))^2+(HIP(i-(Start-1),2)-LKNE(i-(Start-1),2))^2);
b(i-(Start-1),2)=sqrt((LANK(i-(Start-1),1)-LKNE(i-(Start-1),1))^2+(LANK(i-(Start-1),2)-LKNE(i-(Start-1),2))^2);
c(i-(Start-1),2)=sqrt((HIP(i-(Start-1),1)-LANK(i-(Start-1),1))^2+(HIP(i-(Start-1),2)-LANK(i-(Start-1),2))^2);
alfa(i-(Start-1),2)=acos((a(i-(Start-1),2)^2+b(i-(Start-1),2)^2-c(i-(Start-1),2)^2)/(2*a(i-(Start-1),2)*b(i-(Start-1),2)))*180/pi;
end

x=(0:0.04:0.04*(END-Start));
y=(alfa(:,1))';
for i = Start:END
   alfa2(i-(Start-1),1)=x(i-(Start-1));
      alfa2(i-(Start-1),2)=y(i-(Start-1));

end
% Start of the model simulation
sim('model_KJ_gate.slx');
% Choosing of the data arrive
t=Comparison_results(:,1);
D1=Comparison_results(:,2);
D2=Comparison_results(:,3);
% Building of the graphs
figure;
plot(t,D1, t, D2,'r--' , 'LineWidth', 2);
ylabel('angle (deg)');
xlabel('time (s)');
legend('experimental data','model simulation')
grid on;
```