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MOTION MODELING OF THE HUMAN LOWER LIMB, SUPPORTED BY ORTHOSES

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Abstract: *In this paper healthy knee joint motion in sagittal plane and motion of the knee joint, supported by orthosis in sagittal plane were modelled in MATLAB. Models simulate motion during the gait, angles between links, which simulate femur and tibia controlled by Simulink block Model predictive control (MPC). The results of simulation have been compared with several samples of real motion of human knee joint obtained from motion capture systems. Based on this comparison conclusions about positive or negative influence by the active orthosis on the knee joint can be made.*
Key words: Knee joint, modelling, active orthoses

1. INTRODUCTION

Knee joint is one of most difficult joints from the point of biomechanics [1]. Knee joint is a movable connections of the femur, tibia, fibula and patella. Also meniscus, capsular-ligamentous apparatus and muscle-tendinous complexes are included in the knee joint. Knee joint is one of the most complex and vulnerable joints in the human musculoskeletal system. This caused by the fact that at this point articulate the longest levers of the lower limb: the femur and tibia [2].
Knee joint is represented on the figure 1, where: 1, 7 – collateral ligaments, 5, 6 – circular ligaments, 2 – tibia, 3 – fibula, 4 – femur, 8 – patella.
Almost every person in explicit or implicit form faces with injuries of the knee joint.

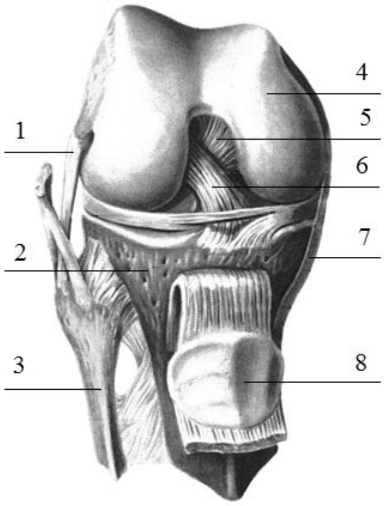

Fig. 1. Right knee joint

Orthoses are used for rehabilitation after knee joint injuries very often, but choosing of orthosis is laborious process, which takes a lot of time. Model, which is considered in this research, allow simplify choosing of orthosis and avoid possible complications.
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]. Despite of variety models of the knee joint, articles, where model of the knee joint is supported by the active orthosis was considered have not been found for this moment.

2. KNEE JOINT MODEL

In this research mechanism, which simulates knee joint motion at sagittal plain was considered. Kinematic scheme of this mechanism is represented on the figure 2.

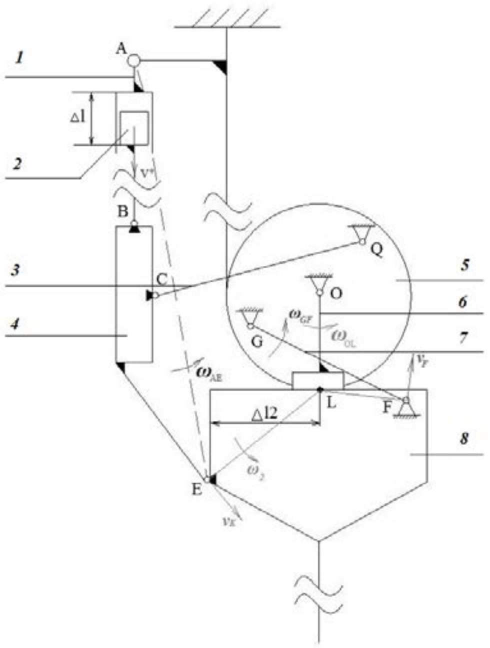

Fig. 2. Mechanism, which simulates knee joint motion at sagittal plain

It's planar mechanism, with one degree of freedom:

$$w = 3 \cdot (n-1) - 2P_5, \quad (1)$$

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.

Then

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

Length of links, which simulate bones and others parameters of mechanism correspond to the parameters of an average man (height – 175 cm, weight – 70 kg), but all of this parameters can be changed in accordance with the parameters of the particular human [8-9].

3. KINEMATICS

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:

$$(x-a)^2 + y^2 + z^2 = R^2, \quad (3)$$

$$(x+a)^2 + y^2 + z^2 = R^2, \quad (4)$$

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:

$$(Z_F - Z_G)^2 + (Y_F - Y_G)^2 = GF^2, \quad (5)$$

$$(Z_L - Z_O)^2 + (Y_L - Y_O)^2 = LO^2, \quad (6)$$

$$(Z_F - Z_L)^2 + (Y_F - Y_L)^2 = (LF + \Delta l_2)^2 \quad (7)$$

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 (point L is also instant center of velocity) 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:

$$(Z_Q - Z_C)^2 + (Y_Q - Y_C)^2 = QC^2 \quad (8)$$

$$(Z_B - Z_C)^2 + (Y_B - Y_C)^2 = BC^2 \quad (9)$$

$$(Z_E - Z_C)^2 + (Y_E - Y_C)^2 = EC^2 \quad (10)$$

$$(Z_E - Z_B)^2 + (Y_E - Y_B)^2 = EB^2 \quad (11)$$

$$(Z_E - Z_F)^2 + (Y_E - Y_F)^2 = EF^2 \quad (12)$$

$$(Z_E - Z_L)^2 + (Y_E - Y_L)^2 = \Delta l_2^2 + LE^2 + + \frac{\Delta l_2^2 \cdot (LE^2 + LF^2 EF^2)}{LF} \quad (13)$$

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

$$(Z_B - Z_A)^2 + (Y_B - Y_A)^2 = (AB + \Delta l)^2 \quad (14)$$

where:
Z_A, Z_B, Y_A, Y_B – coordinates points of links attachment,
AB – distance between points A and B,
Δl – displacement of sliding block along the guiding AB.

4. MODEL OF THE HEALTHY KNEE JOINT IN MATLAB

For modelling motion of the knee joint supported by orthoses, firstly it is necessary to create model, which simulate motion of the healthy knee joint. This model is represented on the figure 3.

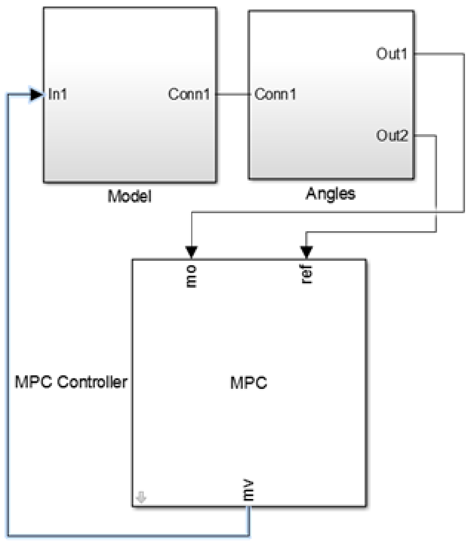

Fig. 3. Model of the healthy knee joint

Parameters of model like: weight, length of links, inertial moments and relative position of the links should be known for modelling. All this parameters are predetermine in block "Model", this block is represented on the figure 4.

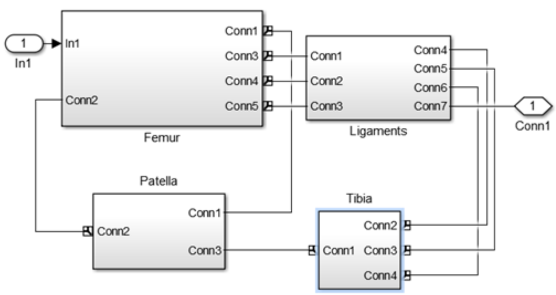

Fig. 4. Block Model

Angle between tibia and femur should be corresponding with real angle, therefore it is necessary to simulate forces in quadriceps correctly. Mathematical calculations of dynamics are automated and performed using block MPC (MATLAB/Simulink). Block MPC controls links, which simulate quadriceps (links 1, 2), and allow to control angle between tibia and femur.

5. MODEL OF THE KNEE JOINT, SUPPORTED BY ORTOSIS IN MATLAB

Assumed that knee joint was damaged, for this purpose links were excluded, which provide stability and controllability of model. This links are “circular ligament” (links 6,7). Herewith model of active orthosis was added in uncontrolled model of knee joint. Orthosis, which is used at the model provides only one degree-of-freedom. Model of the knee joint, supported by orthosis is represented on the figure 5.

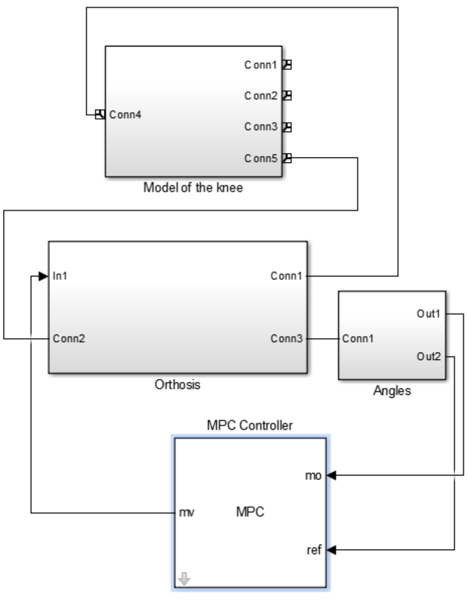

Fig. 5. Model of the knee joint, supported by orthoses

Model simulates motion of the knee joint during the gait and controlled by MPC block, but in this model MPC block controls motion of orthosis, which provide necessary movement of the knee joint.

6. RESULT OF THE SIMULATION

Results of models work, which simulates healthy knee joint, were compared with data of real human gait obtained from motion capture system (Vicon). Comparison is represented on the figure 6.

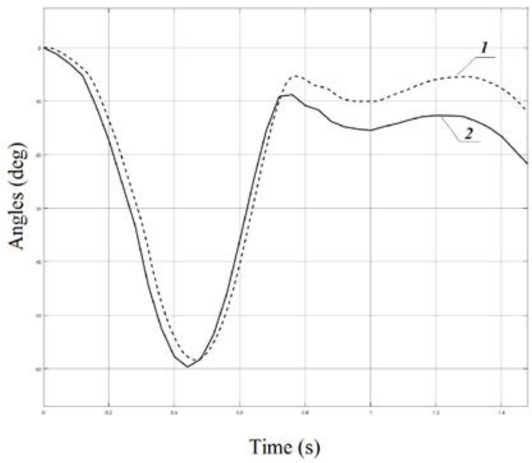

Fig.6. Comparison results of models work, which simulate healthy knee joint (line 1) and data, obtained from motion capture system (line 2)

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

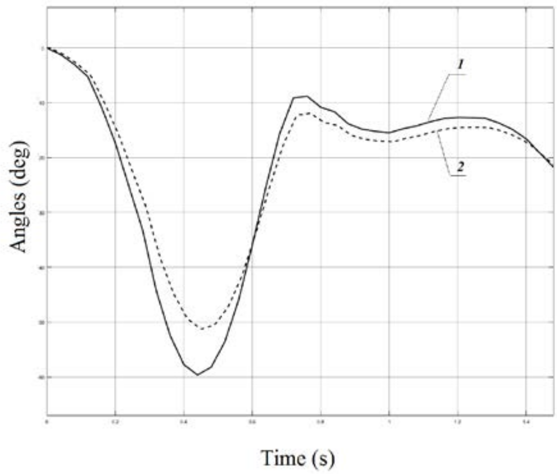

Fig.6. Comparison results of models work, which simulate knee joint, supported by orthosis (line 1) and data, obtained from motion capture system (line 2)

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

7. CONCLUSION

Based on analysis of simulation result, conclusion that general dynamics of movement of the received model corresponds to movements of the real, was made, however there is an error, which can be caused by difference in length of links and their masses. In spite of error, conclusion about ability of orthosis to simulate motion of the healthy knee joint at sagittal plane was made. It means that using of this orthosis for knee joint is advisable during post traumatic period.
At the future research supposed:

- Minimize mistake appearing during the modelling
- Visualize the model
- Explore different types of knee joints active orthoses constructions
- Explore different orthoses fixing places
- Prove the importance of the correct positioning of the orthoses.

Based data was got during exploring different types of knee joints active orthoses and there different fixing places supposed facilitate selection and positioning of the orthosis for each patient.

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ADDITIONAL DATA

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