291. Changes of the human gait after total hip joint replacement surgery

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Abstract. The aim of this work was to determine the effect of a hip joint replacement on human locomotion-support apparatus and movement functions. 3D biomechanical model of human locomotion-support system was developed for comparative analysis of the healthy state and the state after total hip replacement operation. The effect of shift of hip joint replacement centre position on human movement and muscles activity patterns was determined by using computational and experimental methods. The results of analysis obtained on the basis of this model and method are presented: it is shown that the change of position of hip joint replacement elements (cup and sphere) has substantial effect on human walking pattern.

Keywords: human locomotion-support apparatus, total hip joint replacement, movement functions, gait analysis, computer biomechanical model

Introduction

Rehabilitation is one of the most important research areas of medical biomechanics. Quite often research is carried out identifying causes for disorders of patients' locomotion-support apparatus and creating methods and means to restore disordered. Patients who have suffered injuries of the locomotion-support apparatus are usually given endoprostheses. There are hundreds of thousands of total hip joint replacement operations performed in the world each year.

One of the most actual problems during joint replacement surgery is to assure accuracy of insertion of the elements of total joint replacement, because due to deviation of the joint centre human movements do not correspond the one possessed while being healthy. Medical practice shows that incorrect position of components may cause a shorter endoprosthesis usage time [1-3], as well as suffering of patients' health: human movements do not conform to parameters present at healthy state, longer rehabilitation time etc. [4, 5].

A lot of reasons can determine such inaccuracy - sometimes it may be difficult to restore the normal joint anatomy correctly due to anatomical changes of linking bones of joints caused by illnesses or injuries, still cases when surgeons choose implant components or put them in incorrectly during surgery are quite often.

There are various methods and means used to identify exactly the position of natural hip joint centre before the operation as well as to put the correctly chosen and correctly oriented implant into the designated place during operation.

Surgeons usually determine the hip joint centre position according to one or two X-ray pictures. Prognostic and functional methods are used to determine the hip joint centre position in this instance. With the help of prognostic methods hip joint centre is determined approximately according to anatomical marks [6-8]. For this task hip joint X-ray pictures are needed before the operation. With the help of the functional method joint centre position is determined by observing and recording motion trajectories of a control point (or several points) on femur with respect to pelvis and by putting the received trajectories into an assumed sphere which will have the same centre as the joint centre [9-11].

During the preparation to and surgery itself various auxiliary equipment is used – guides, gauges, templets and special tool for bones processing, delivered with hip replacement unit by its manufacturer. In more advanced cases virtual systems of planning and simulation of the surgery on the basis of 3D computer models of bones connected by the joint to be replaced are used [12-16]. Nevertheless none of means mentioned above is able to provide the information about what was the exact result of operation or even to prompt what inaccuracy (the size and direction) in positioning of one or both elements of total joint replacements should be preferable in case of necessity of choice.

There again, day after day contemporary science may research more deeply an even wider problem area. Modelling of biomechanics that analyses live organisms from the mechanical point of view is a means for solving specific problems that usually do not allow a direct intervention inside the researched object. Mathematical and computer modelling is especially suitable here and may be easily applied to research the human locomotion-support apparatus, i.e. to identify the strength of its elements, static and dynamic properties; to construct ergonomic environment etc.; to design and produce medical equipment (prostheses, orthopaedic and orthodontic devices); to develop, enlarge or compensate human physical and mental capacities (to create and develop sports equipment, training equipment and methodologies of working with them).

When modelling human motion several types of one-dimensional, two-dimensional or three-dimensional (3D) models are used [17-23]. In rigid body models that are used most often for gait modelling the whole human or certain body parts are described as rigid segments, and their motions are defined as corresponding moments in joints. Mass-Spring models, made from one or several masses connected with each other by elastic elements, are usually used for modelling of running, jumps or other repetitive motion; Wobbling-Mass and Mass-Spring-Damper models are used to model impact load effect on human motions. Musculo-Skeletal models are also made of rigid segments, but in this case their motion is governed by muscles (certain sub-models) – such models correspond to human locomotion-support apparatus most. For more sophisticated research of locomotion-support apparatus a specialized biomechanical analysis software (AnyBody, LifeMOD etc.) can be used that evaluate geometrical (anthropometrical) data of locomotion-support apparatus, joints motion ranges, stiffness and damping in them and in muscles, ligaments and tendons may be created, calculation of forces that influence joints or body parts (including muscles) during any movement – walking, riding a bicycle, etc. or simply when the human being is treated as unmovable passive body, but in most cases they are able to simulate and to analyze the present situation.

Thus, having the aim to determine the effect of hip joint replacement on human locomotion-support apparatus and movement functions an attempt was made to create computer biomechanical model allowing to simulate hypothetical medical situation corresponding the shift of a hip joint centre during total hip replacement operation and to analyse its sequences on human locomotion-support apparatus and movement functions.

Research methodology and model for research of movement of humans with total joint replacements

For evaluating the effect of inaccuracy of the surgical operations of changing injured joints with implants the methodology is suggested that includes experimental research as well as computer modelling. The primary data are received experimentally, with a 3D motion capture and analysis system, and an effect of the shift of a hip joint centre position is evaluated by computing movement trajectories of certain control points of a healthy person and the same person after operation by using a computer model of locomotion-support apparatus. The suggested methodology consists of the following stages of experimental research and computer modelling:

- a moving (healthy) person is filmed with 3D motion capture and analysis equipment: movement trajectories of body control points, laws of changes of joint angles, consistent patterns of body segment movement, speeds and accelerations are determined;
- according to the anthropometrical data (height, weight, body proportions) of the researched person a computer biomechanical model is created with the help of biomechanical analysis software that corresponds to his/her locomotion-support apparatus and includes absolutely stiff bones, joined with joints of certain stiffness, damping and range of motion, and muscles with which the model could be made to move;
- when solving the inverse dynamic problem of movement of a healthy person (when trajectories of movement of the body control points or the laws of change of joint angles are assigned to the computer biomechanical model) the consistent patterns of the muscles activity are determined that would ensure the model's movement that corresponds to the one measured experimentally;
- when solving forward dynamics problem (when movement of the same computer biomechanical model is formed by applying the consistent patterns of the activity of virtual muscles determined during the previous step), computer model movement is received again (trajectories of body control points), but in this case it is ensured not by trajectories of control points but by the activity of virtual muscles that simulates the work of real muscles. The more precise the computer model is the better correspondence of trajectories of control points, measured experimentally and calculated by the method of forward dynamics modelling, will be;
- total hip replacement operation outcome is computed imitating a certain inaccuracy of the operation, i.e., the centre of the inserted hip joint implant in the computer model is shifted – moved in space by a known magnitude in a known direction, and a forward dynamic analysis is performed again providing the corrected model with the laws of muscles activity of a healthy person. The movement parameters, received on the basis of the adjusted model corresponding to the person who has been operated on, show the effect of inaccuracy of the operation.

Such research is carried out with respect to the fact that usually it is characteristic of a human organism to "remember" certain consistent patterns of its activity, including the change of muscle activity when performing repetitive motions (walking), and to try to walk after the operation in the same way as in a healthy state.

To implement the method described above, a human biomechanical model designed for the case oriented modelling software that up till now had been used only for the description and visualisation of the current state has been adapted to perform comparative analysis of a healthy state and a state after a total hip joint replacement operation. A computer biomechanical model that corresponds to a healthy person is supplemented by putting an implant instead of a corresponding hip joint. The implant consists of a socket that is fastened in the pelvis bone, and a stem with a sphere, fastened in the femur bone (Fig. 1). Due to the absence in the case oriented modelling software of the implant model suitable to perform computations while changing the position of the joint centre independently of the positions of the joint elements masses centres and the origins of coordinates systems, a special implant model has been created that is suitable for LifeMOD software (Fig. 1, b and c).

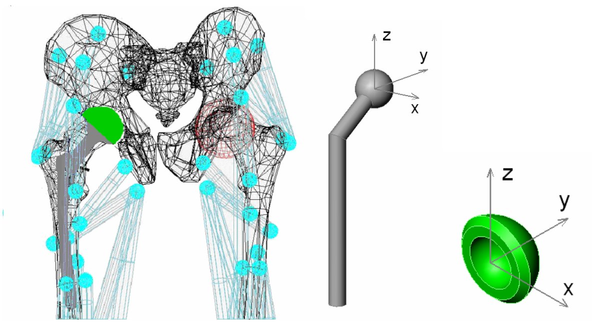


Fig. 1. Human biomechanical model: a – fragment of model of lower body with implant; b and c – models of elements of hip joint replacement

Results and discussion

Initial movement trajectories of body control points (markers) were determined when filming a walking person (Fig. 2), and these trajectories (Fig. 3) were automatically transmitted into a computer forming a table of change in time of all three spatial coordinates of all control points. Based on this data, the laws of change of joint angles and body segments motion, velocities and accelerations of the control points have been determined and stored in a database by means of 3D motion analysis software. Experimental research has been performed in biomechatronics laboratory of Kaunas University of Technology by means of 3D motion capture and analysis system Qualisys, and computations – in Engineering Mechanics department of KTU by means of specialised kinematic-dynamic analysis software LifeMOD.

According to the anthropometrical data of the researched person a computer biomechanical model has been designed by means of LifeMOD, which corresponds to his/her locomotion-support apparatus and includes only the lower body – bones, joints connecting them and muscles that enable the movement to be investigated. In case of gait analysis such a model includes: pelvis, both femurs, tibias, fibulas, bones of the left and right feet, connected by hip, knee and ankle joints, and main muscles of both lower limbs: Adductor Magnus, Gluteus Maximus, Biceps Femoris, Gastrocnemius, Iliacus, Soleus, Tibialis Anterior, Semitendinosus, Vastus Lateralis, Rectus Femoris, Vastus Medialis,Gluteus Medius (Fig. 4).

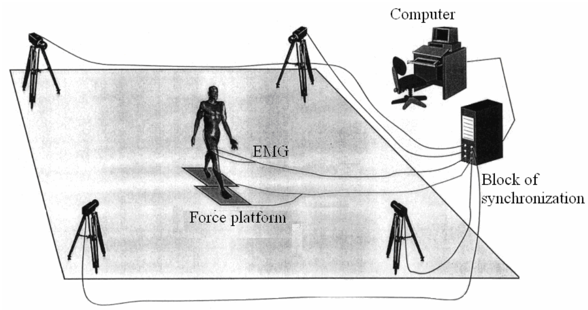


Fig. 2. 3D motion analysis system

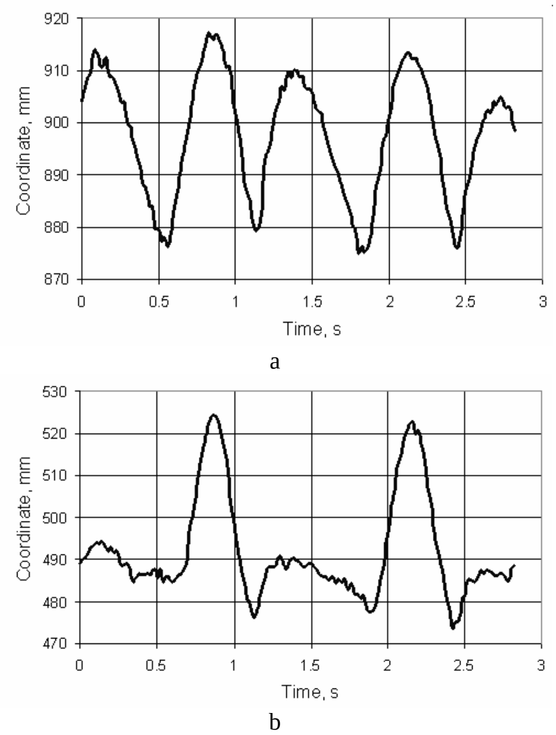


Fig. 3. Change of Y-coordinate of control points (markers) in time: a) of left side of pelvis bone; b) of left knee joint

Fig.4. Computer biomechanical model of lower body part to perform gait analysis

A walking cycle of four full steps – two steps taken with the left, healthy leg, and two steps taken with the right leg that has a hip replacement – is researched (duration of the whole cycle is approximately 2 seconds; duration of each step is approximately 0.5 seconds).

When solving an inverse dynamics problem (assigning movement trajectories obtained experimentally to the model control points) basing on a model that corresponds to a healthy person, the laws of activity of the muscles that ensure the measured movement have been calculated (Fig. 5), and stored in a database.

When solving the forward dynamics problem, the previously calculated muscles contraction forces, or, to be more precise, their change during the modelled motion, were prescribed to the model (of a healthy person again). Thus the movement of a computer biomechanical model that corresponds to the measured one has been obtained (Fig. 6), but in this case it was generated not by the trajectories of the control points, but by the activity of virtual muscles that simulate the work of real muscles.

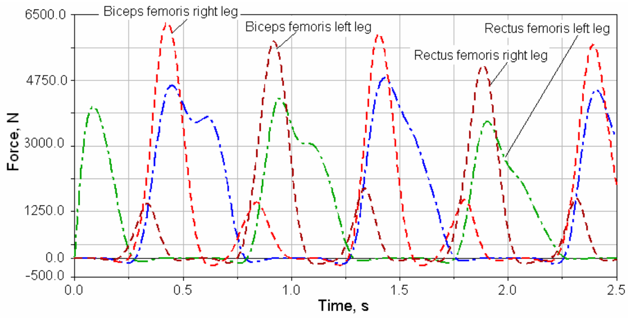


Fig. 5. Change of muscle power during the walking cycle calculated during inverse dynamics analysis (both straight thigh and two-headed muscles)

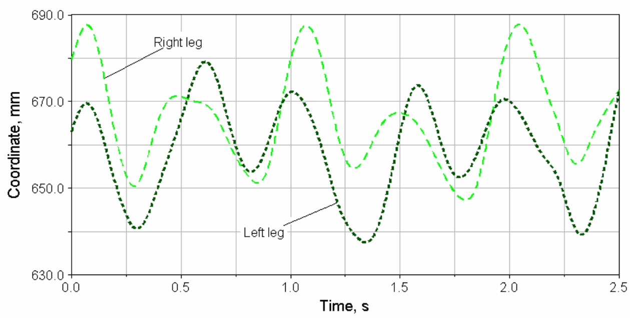


Fig. 6. Forward dynamic analysis. Change of Y coordinate of control points (weight centres of left and right thighs) during the walking cycle

Seeking to determine the effect of the shift of a hip joint replacement centre position on the human movement and muscles activity patterns, the computer biomechanical model has been adjusted thus imitating a certain inaccuracy of the hip joint replacement operation. Than the forward dynamics analysis of motion has been carried out again assigning to the corrected model laws of activity of the muscles of a healthy person. Gait parameters received in such way have been compared with the gait parameters obtained on the basis of a model that corresponds to the healthy person.

Computations have been made by changing the position of hip joint elements (and the hip joint centre also) in respect of corresponding bones (socket – pelvis bone, sphere – femur bone) 2, 4 and 6 mm in the vertical direction (both upwards and downwards) as shown in the Fig. 7, b-e. In this way a dual medical situation has been modelled: when pelvis bone is "raised" and "lowered" (tilting correspondingly around the healthy hip joint), and when femur bone is shortened or lengthened (in all cases the points of joining muscles to bones stay unchanged).

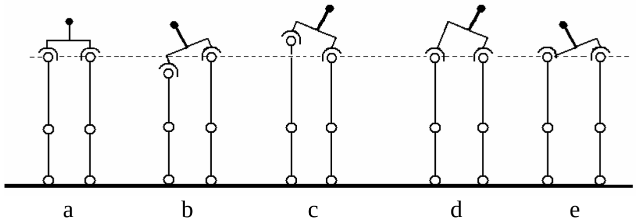
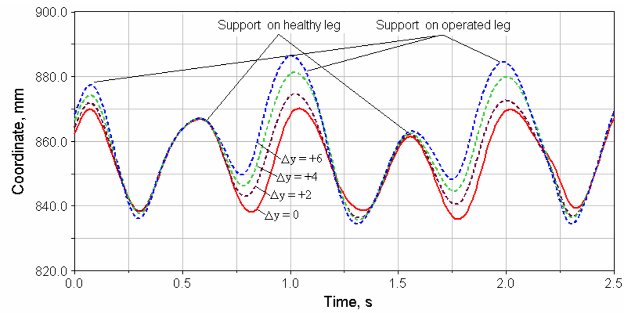


Fig.7. Position of hip joint elements (and hip joint centre) with respect to corresponding bones (socket – pelvis bone, sphere – femur bone) in vertical direction

In the Fig. 8 the curves of change of the Y-coordinates of three control points during walking cycle are given for the control points (centres of the healthy and replaced hip joints and pelvis mass centre), corresponding various initial position of hip joint implant elements. In the Fig. 9 the change of the force of the main muscles that form the gait during the researched walking cycle (two-headed, straight thigh and hip muscles) when shifting the replaced hip joint centre is shown.

After the variational computations it was determined that the change of the position of implant elements (socket and sphere) with respect to corresponding bones in horizontal (transverse) plane within the range of ± 6 mm does not have effect on the trajectories of pelvis mass centre and the centres of the healthy and replaced hip joints. A shift of more than 6 mm of the position of the socket or the sphere in vertical direction causes radical changes of control point trajectories, i.e., the maximum permissible shift of hip joint centre in vertical direction is 6 mm.

The trajectories of the healthy joint centre and pelvis weight centre during the walking cycle having shifted operated hip joint sphere and socket in opposite directions by the same value are coincident with each other. Changing the implant sphere position with respect to the femur bone as well as the implant socket position with respect to the pelvis bone in the phase of support on the healthy leg they also stay unchanged, and in the phase of support on the implanted leg they change depending on the model modification in such a way that the pelvis bone would stay in a horizontal position when walking, i.e., when the socket is lowered and the sphere is raised the upper trajectory points rise approximately 2.5 times more than the value by which the model was modified, and when the socket is raised or the sphere is lowered they fall approximately 1.5 times more than the value by which the model was modified.



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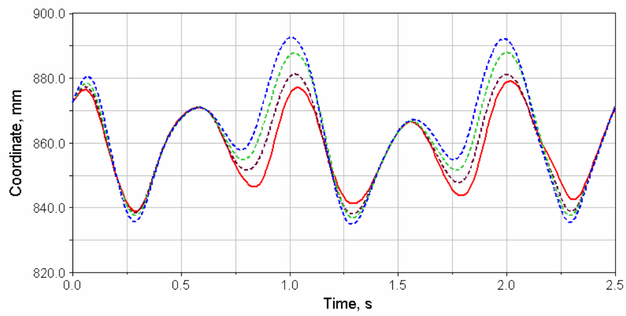

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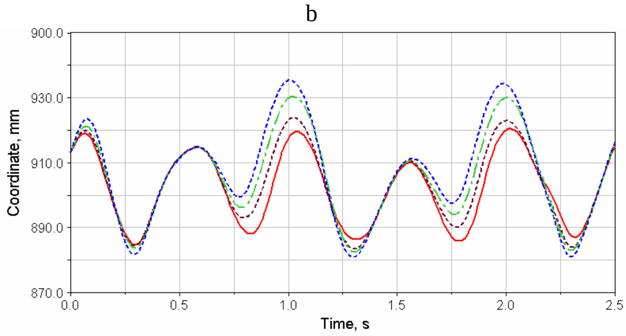

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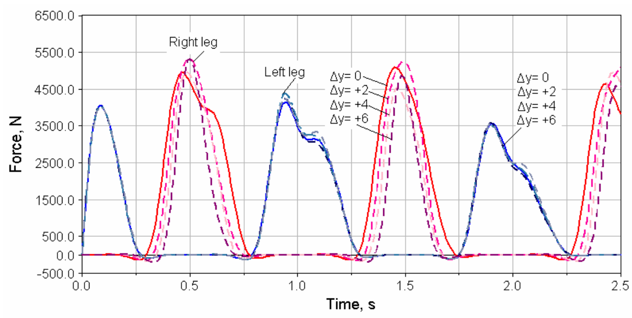
Fig. 8. Results of forward dynamic analysis of the human gait. Curves of Y-coordinate's change of lower body control points: a - healthy joint centre, b - implanted joint centre and c - pelvis mass centre during walking, received when shifting the hip joint implant centre by 2, 4 and 6 mm vertically up-wards with respect to the femur bone (femur bone lengthening, Fig. 7, c), the solid line marks the curves when the hip joint replacement centre corresponds to the natural joint centre



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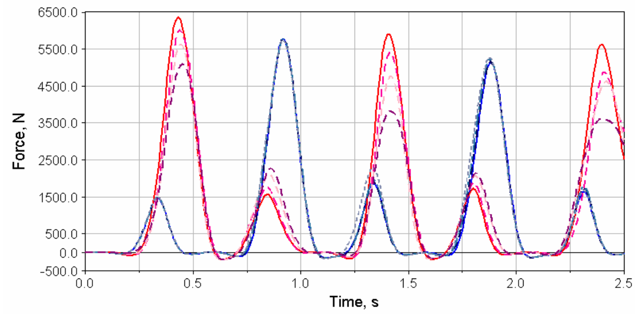

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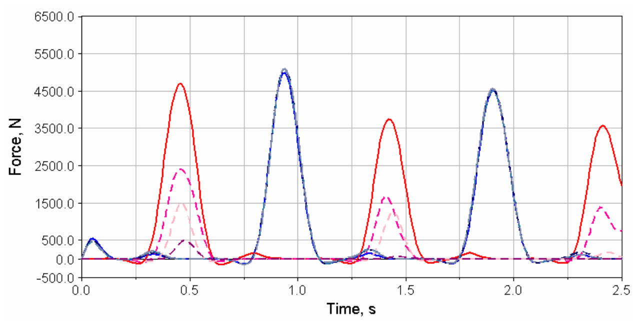

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Fig. 9. Results of forward dynamics analysis of the human gait: curves of change of muscles force: a) Rectus Femoris, b) Biceps Femoris and c) - Iliacus during the walking cycle of two steps, received when shifting the hip joint implant centre by 2, 4 and 6 mm vertically upward with respect to the pelvis bone (situation shown in Fig. 7, e); the red solid line marks the change of power of a certain muscle, when the hip joint replacement centre corresponds to the natural joint centre, and the blue solid line marks the change of power of the corresponding muscle in the healthy leg

When the implant sphere position is changed with respect to the femur bone in both directions (i.e., shortening or lengthening the femur) in the phase of support on the leg with the hip replacement the replaced joint centre trajectories change in an analogous way, i.e., when the femur bone is lengthened the upper points of the trajectory rise approximately by 2.5 times more than the value by which the model was modified, and when it is shortened, they fall by 1.5 more than the value by which the model was modified, and when the implant socket position is changed with respect to the pelvis bone, in the phase of support on the leg with the hip replacement, trajectories of this point change in same way as in the case of changing the sphere position with respect to the femur bone, but a little less (up to 1.5 times), besides, trajectories of this point change also in the phase of support on the healthy leg (when the socket is lowered, the upper points fall by the same value, and when it is raised, they rise also).

Conclusions

1. 3D global biomechanical model of human locomotion-support system for the case oriented modelling software for the research of biomechanical models has been adapted for performing comparative analysis of the healthy state and the state after the total hip replacement operation and methodology was created to determine the effect of shift of hip joint replacement centre position on human movement and muscles activity patterns.
2. It has been determined that the change of position of hip joint replacement elements (socket and sphere) in horizontal (transverse) plane does not have substantial effect on human walking pattern, and the change of position of implant elements in vertical direction more

than 6 mm from anatomical value changes the pattern very noticeably.

3. Trajectories of the healthy joint centre and pelvis mass centre stay unchanged when changing the position of implant sphere with respect to the femur bone as well as the position of implant socket with respect to the pelvis bone in the phase of support on the healthy leg, and in the phase of support on the leg with hip replacement they change depending on the model modification in such a way that the pelvis bone would stay in horizontal position when walking, i.e., when the socket is lowered and the sphere is raised, the upper points of the trajectory rise approximately 2.5 times more than the value by which the model was modified, and when the socket is raised or the sphere is lowered, it falls approximately 1.5 times more than the value by which the model was modified.
4. After changing the implant sphere position with respect to the femur bone, in the phase of support on the leg with the hip replacement, when the femur bone has been lengthened, upper points of the trajectory of replaced hip centre rise approximately by 2.5 times more than the value by which the model was modified, and when the femur bone has been shortened, they fall approximately by 1.5 times more than the value by which the model was modified. When changing the implant socket position with respect to the pelvis bone, in the phase of support on the leg with hip replacement, joint centre trajectories change in an analogous way as in the case when sphere position is changed with respect to the femur bone, but a bit less (up to 1.5 times), besides, trajectories of this point in the phase of support on the healthy leg change: when the socket is lowered, upper points fall by the same value, and when is it raised, they rise.

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