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# Orthopaedic fixator with adaptable kinematics for functional treatment of periarticular fractures of the knee joint – experimental research, computer simulation, first clinical trial

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An orthopaedic stabiliser to be used for the treatment of periarticular fractures of the knee joint is presented. The design of the device is documented by experimental research of the knee joint kinematics. Experimental and simulation research suggests the use of a four-bar linkage mechanism. This research has also made it possible to define the range of adjustment to adapt the kinematics of the stabiliser to the individual characteristics of patients.

This paper presents the results of the first trials for clinical stabiliser.

## 1. Introduction

An inseparable side-effect of a continual development of motorization is a larger number of traffic accidents. These usually result in trauma to organs responsible for movement, and this is one of the driving forces behind the search for new methods to treat such cases. The process of constructing stabilizers which aid this treatment is preceded by modelling and stimulation. The movements occurring in the knee joint have a complex character and they cannot be approximated by a movement in a simple hinge joint. While treating the periarticular fracture, the task of the stabilizer is to imitate the physiological movement in the articulated knee joint. This is the basis for functional treatment which is a new method in dealing with periarticular fractures using external osteosyntesis. Recently, there has been some rapid development of new orthopedic designs of external joint stabilisers. The new designs are aimed at meeting the following clinical requirements:

- functional treatment must be possible: the natural movements of human joints must be imitated in treating periarticular fractures, and micro-movement must be possible within the fracture (taking place in a particular direction, and within a range precisely determined),
- biologically-friendly materials must be used, and the stabiliser must be easy to install,
- stabiliser must be "firmly" set onto the bone material, resistance to osteolysis must be ensured,
- easy bone repositioning must be provided, it must be possible to attach manipulators so as to assist the repositioning process,
- a measuring system must be installed to assist the synostosis process, e.g., using neuron networks.

Each of these requirements and their clinical importance have been thoroughly analyzed in a number of studies [1], [2]. This paper focuses on the issue of functional treatment of periarticular fractures of the knee joint. This treatment allows bone movement within the affected knee joint as early as possible. For this purpose, the kinematics of the knee joint and of the stabiliser joint must be closely matched.

The number of publications on the knee joint are rather large. In studies [3]–[5], the knee joint dynamics is analysed, taking into account the geometry of the bone, as well as the spatial configuration and the non-linear characteristics of the joint ligaments. In studies [6]–[8], the forces and stresses generated in the knee joint are analyzed. Studies of knee joint dynamics and its analysis can also be found in papers [9]–[12]. The authors of this papers are of the opinion that theoretical content of their studies is important; however they provide no clear indication of a possible practical application of their findings. To the best of the authors' knowledge, there is no stabilizer with adaptable kinematics that is available for treating periarticular fractures of the knee joint. Therefore, we believe that the subject of this paper is a novelty in its nature.

## 2. Experimental research. Analysis of results

In the process of designing a knee joint stabiliser for treating periarticular fractures, some of the preliminary research was experimental in nature. The difficulty in designing such a device lies in the fact that the stabiliser must closely follow the joint's natural kinematics. This depends not only on the geometry of various joint surfaces, but also on the working of the ligament system [7] (mainly of the cruciate and lateral ligaments). To the best of the authors' knowledge, no literature on kinematics is available to provide a sufficient background for imitating the natural knee joint kinematics in stabiliser design. Therefore, it was necessary to undertake experimental research.

The purpose of the research was to provide a description of the tibial bone movement relative to the femoral bone. The research is based on the roentgenography that allows the observations of X-ray images of the joint at different angles of flexure. It was assumed that a 2-D analysis of the joint movements would be sufficient to solve the problem.

A modern X-ray imaging equipment with low levels of radiation was used for the observations. This equipment enables real time X-ray imaging of joint movement, and makes it possible to create documentation in the form of individual images. For each patient, a package of 30 digital images was made to create a graphic record of the knee joint movement (figure 1).

Fig. 1. X-ray images for experimental research in knee joint kinematics

The examination involved a group of 20 patients of both genders at different ages and with a different bone structure. The results of the analysis made it possible to estimate the scope of variations in knee joint kinematics for a general population.

To find the relative movement of the bone, WiseIimage 5 software was used. The purpose of the research was to map the movement of the tibia and the femoral bone by analysing a succession of images within a stationary system of co-ordinates.

Then, elementary transformation was used to map the movement of the tibial bone relative to the femoral bone expressed in the related local system. This movement was described as the movement of certain point positioned on the tibial bone as a function of the angle of joint flexure. In the next step, using the description of the relative bone movement, an algorithm was created to automatically generate the trajectories for any selected point positioned within the tibia. Using the optimisation procedures, we looked for a position of new point which traces a trajectory closest to the arch (figure 2a). The decisive variables in the task of optimisation were the position of the points $p'$ and $A$, and the length of the segment (radius) $AB$. As a limiting condition it was assumed that $y_A = y_B$. The objective function was the minimum of the sum of the squares of the distances between the trajectory of the point $p'$ and the arch traces by the point $B$. By treating the point $A$ as the centre of rotation for the point $B$, the optimisation task was aimed at finding a position of the points $A$ and $p'$ in which the objective function would reach the minimum.

As a result, we could observe certain characteristics which were shared by all patients. If the tibia is analysed as a solid, then the point $p'$ makes a circular motion, but also the tibia rotates about that point (figure 2b). This rotation is referred to as polar rotation. By analysing the joint movements in different patients, we arrived at different lengths of $AB$ within the range of 60–100 mm.

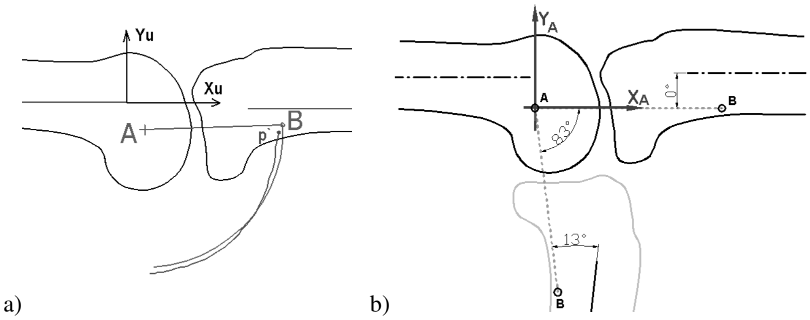

Fig. 2. Diagram of the knee joint movement

This way we were able to determine the kinematics of the knee joint for all the patients as a double joint with two centres of rotation: $A$ – on the femoral bone, and $B$ – on the tibial bone, whose segments rotate at the angles of $\alpha_A$ and $\alpha_B$ which are uniquely related to each other in each individual person. The sum of the angles $\alpha_A + \alpha_B = \alpha$ (figure 4) is the total flexure angle of the lower leg relative to the femoral bone. Figure 3 presents sample charateristics of the changes to the angle of polar rotation $\alpha_B$ as a function of the joint flexure angle $\alpha$ (for four cases).

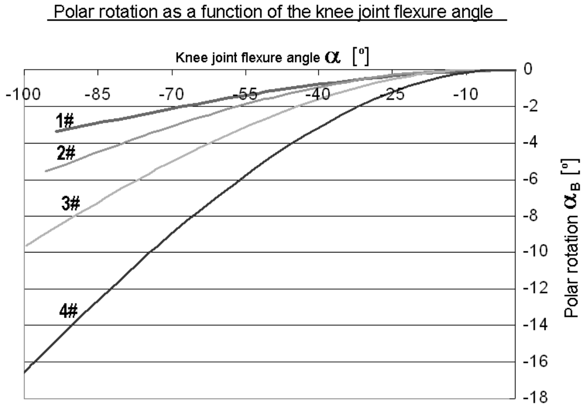

Fig. 3. Polar rotation as a function of the knee joint flexure angle,
($i$#: $i$ = 1, 2, 3, 4 – cases numbers)

The inter-relation of these movements can be realised using the variable-parameter four-bar linkage mechanism (figure 4a). The mechanism is simple and allows a number of regulating options to change its kinematics.

In this context, it was necessary to find how the joints *C* and *D* are positioned so that the four-bar linkage mechanism can correctly reflect the polar rotation motion for each patient. For that purpose, the position of the arm of polar rotation was optimised. The minimum of the sum of the squares of the difference of the values of the studied polar rotation $\alpha_{BK\,i}$ and of the rotation necessitated by the mechanism $\alpha_{B\,M\,i}$ is assumed to be an objective function.

The decisive variables were the positions of the points *C* and *D*. As a result of this procedure, the optimum ranges of the change to the position of those points were found. Figure 4b shows the diagram of the changes to the position of the joints.

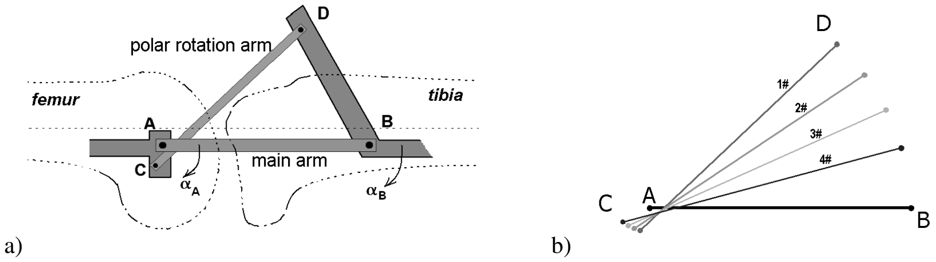

Fig. 4. Diagram of the four-bar linkage mechanism (a);
diagram of the changes to the positions of the joints *C*, *D* (*i*#: cases numbers) (b)

Based on this analysis, the variable-parameter four-bar linkage mechanism has been suggested to imitate the kinematics of the knee joint. By changing the length of arm *AB* and by regulating the position of the joints *C* and *D* we can adapt the kinematics of the mechanism to the patient's individual characteristics.

## 3. Simulation study, analysis of parameter sensitivity

Simulation studies were carried out using the 2-D Working Model system of MSC software. The system allows easy kinematics simulation of complex 2-D mechanisms. To begin with, a 2-D model of the knee joint was created whose movement was defined using the results of experimental research. The next step was to build a model of the four-bar linkage mechanism by using the results of the optimisation tasks discussed above. This simulation confirmed that the kinematics of the model was correct.

In the next stage of the study, the position of the mechanism model was changed relative to the knee joint. The aim of this study was to check the impact of the mechanism positioning inaccuracies on the correct functioning of the stabiliser. This is to be fitted under the particular conditions in the operating room, and currently there exists no navigation tool to facilitate the positioning of the mechanism.

The bones are practically rigid, the meniscus – a cartilage positioned between the bones – is slightly susceptible to compression, however it is rather thin and therefore its compressibility is low, so a possible extent of bone convergence in the knee joint is small.

In view of these differences it was necessary to carry out an analysis of parameter sensitivity. For the purposes of this paper, the authors understand the term of "parameter sensitivity" as the calculation of the characteristics of the change of the sum of the squares of the distance between the knee joint trajectory and the mechanism trajectory. The parameter is the distance from the right position stated in two directions. The calculated sum of the squares of the distances between the knee joint trajectory and the mechanism trajectory is presented in figure 5.

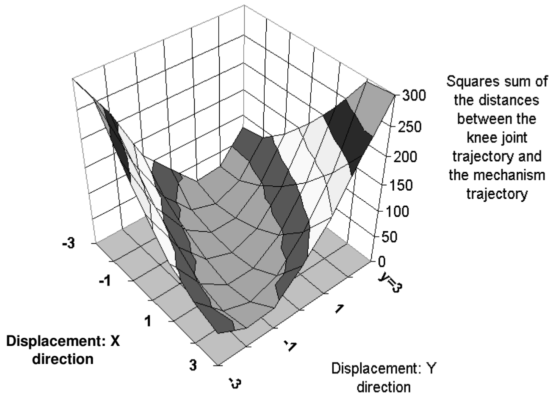

Fig. 5. Parameter sensitivity of stabiliser positioning

The results of the analysis show that finding a right joint position in the mechanism has a crucial impact on the stabiliser functioning. The slight compressibility of the joint gives some chance of approximating certain movements and of allowing some slight load on the bone in accordance with normal physiological movement, however, these values are small.

## 4. Concept for a construction solution

The stage of prototype construction was preceded by the design of a virtual model (figure 6). The Catia system was used for that purpose.

The stabiliser makes it possible to move the lower leg relative to the thigh throughout the treatment. This movement is very similar to the natural physiological movement, so the union of the fractured bone can be restored without interruption, and the postulate of functional treatment is realised. Moreover, this makes it possible to make adjustments which can bring the movements guided by the stabiliser in line with the natural, physiological movements of the joint, with a degree of inaccuracy which can be compensated for by the natural compressibility of the joint.

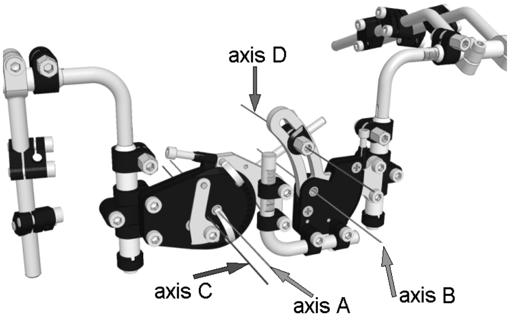

Fig. 6. Virtual Catia model of knee joint stabiliser

The physiological movement is executed by active joints which allow movement within a limited, adjustable range. It is possible to block the stabiliser in each selected position without changing the selected range. The range of movement can be changed by settings of 10° each. The range of joint flexure is $\alpha \geq 130^{\circ}$, i.e., $\alpha_A = 100^{\circ}$ for the main joint *A*, and $\alpha_B \geq 30^{\circ}$ for the polar rotation of joint B. The value of the polar reflection depends on the individual characteristics of the knee, and therefore the actual range of joint flexure may vary from patient to patient.

All elements of the stabiliser are symmetrical and may only be used in this configuration. During fracture treatment, the stabiliser should only transmit loads resulting from the flexing of muscles and ligaments, the weight of the part of the leg below the fracture and of accidental loads. The stabiliser is not suitable for transmitting the load caused by the weight of the body resting on the leg while walking. This results from the distribution of forces within the joint, depending on position [13]. The results obtained with the stabiliser tested on the artificial models of knee joint confirm the theory.

## 5. First clinical trials

The stabiliser for the functional treatment was used for the first time in the Clinic of Orthopaedics and Rehabilitation of the Warsaw Medical Academy in order to treat three patients with periarticular fractures of knee joint. The results achieved were much better than in treating this type of fractures by means of classic methods. During the time of treatment the range of physiological movement of knee joint was increased gradually up to the 90-degree bending angle. Implementation of functional treatment shortened the time of periarticular fracture treatment up to 8 weeks, and also it restored the full function of the knee joint.

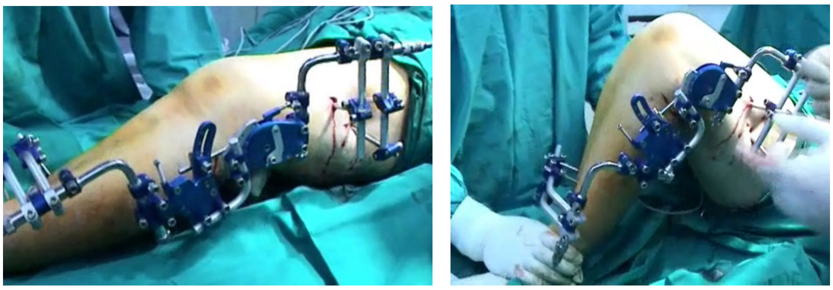

Fig. 7. First clinical stabiliser trials

## 6. Conclusions

The paper presents the concept of an orthopaedic stabiliser solution to be used for treating periarticular fractures of the knee joint. The design of the device is documented by experimental research of the knee joint kinematics. Experimental and simulation research suggests the use of a four-bar linkage mechanism. Experimental research has also made it possible to define the range of adjustment to adapt the stabiliser kinematics to the individual characteristics of patients. A sensitivity analysis proves that the stabiliser must be positioned very precisely during installation.

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