Application of Genetic Algorithms as optimization methodology in the design of orthosis

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Abstract

The Institute of Biomechanics of Valencia (IBV) has developed a new concept of orthotic knee joint, specially designed to improve the comfort and the protection of the knee ligament. This joint follows accurately the pathway performed by the Instant Helical Axis (IHA) of the knee, at the place in which the knee joint should be located. Genetic Algorithms Methodology has been applied, as a new mathematical tool to solve this complex optimization problem. This methodology allows manufacturing optimal joints in a customized form. The research and development has been performed in the frame of the European project proposal Nº: IST-2001-37751, with the acronym of GAIT. The aim of this project is to provide a new approach to active orthotic functional compensation and biomechanical evaluation of knee and ankle joint disorders.

Keywords: Functional orthosis, orthotic design, knee joint models, rehabilitation and customization.

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1. Introduction

Although the main purpose of any lower limb orthosis is to provide stability or to correct and unload the lower extremity during functional tasks, the external joints built-in it should be designed to be reasonably compatible with physiological joint motion. There are several advantages to reproduce accurately the human knee motion in an external joint assembly:

- Reduction of pistonning forces. The reduction of the misalignments between the orthotic and human knee joint reduces the up and down migrations of the orthosis frame, therefore the pistonning and shear forces are also reduced. This kinematics compatibility enhances the comfort to the orthotic user.
- Better ligament protection. This improvement is provided by the reduction of unwanted forces. Consequently the user safety is increased by using this optimal joint.

Fitting a knee orthosis is particularly challenging because of the complexity of the joint's coordinated movement. Several tests and studies have been published with the purpose of evaluating different models of orthotic knee joints, William D. et all [1]. From these researches, it is possible conclude that the current orthotic knee joints, commercially available in the world, do not move in a physiological manner and do not follow properly the human knee motion. Therefore, there is a need to improve the concept of orthotic knee joint.

2. Objective

The aim of this study is the design of an external knee joint based on an optimal four-bar mechanism able to reproduce accurately the motion of the user knee. This external joint will avoid the unwanted forces generated by kinematics incompatibility between the orthotic joint and natural knee joint. The optimization will be performed by using Genetic Algorithms methodology.

3. Methodology

3.1. Biomechanical knee models

To be able to design an optimal joint it is needed to quantify the human knee movement. The kinematics of the knee has historically been difficult to quantify. Anatomic rotations and translations are subject to axis alignment difficulties which inhibit comparisons between subjects. Two biomechanical models of the knee have been used to determine the knee kinematics: Kurosawa-Walter et al [2] and O'Connor [3].

The **Kurosawa-Walter et al.** model is based in considering the medial and lateral femoral condyles as spherical surfaces. If so, the centres of the spheres could be used as reference points. To develop this model of knee motion it is necessary to know the medial and lateral condyles radius and the distance between the "centres of the spheres".

Figure *1* shows the radius and locations of condyles spheres and the direction of the axes that are considered in the model. With this model is feasible to obtain the Instant Helical Axes (IHA), which represents the three-dimensional motion of the knee (

Figure 2).

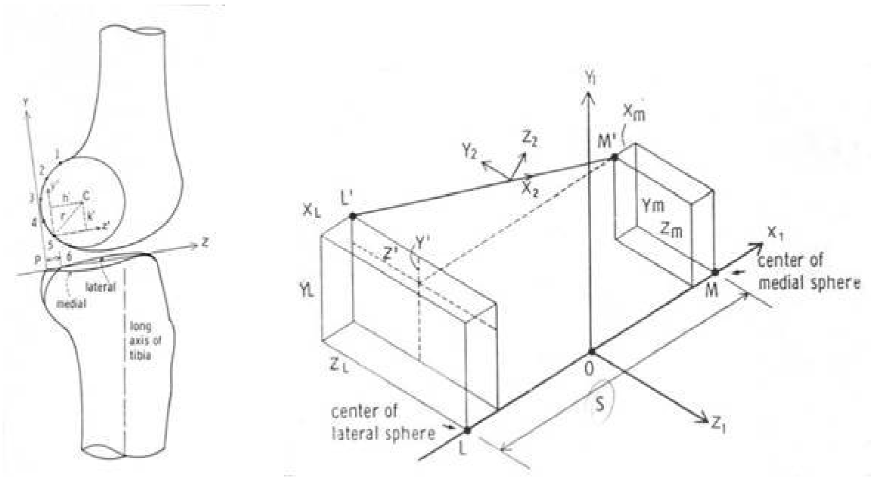

Figure 1: Condyle Radius (left); Lateral and medial sphere centres (right)

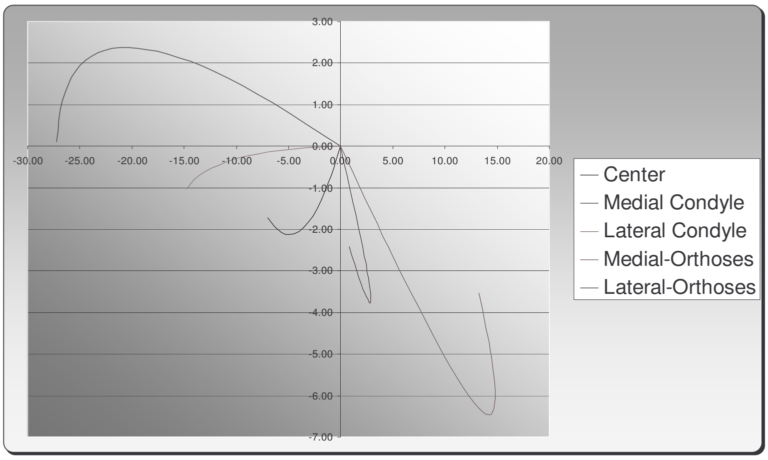

Figure 2: Z-Y Movement of several points in the Instant Helical Axes of the knee

Based on this model the design principle is that the external joints should move the imaginary transverse axis of the femur in the correct path, relative to the tibia, on the medial and lateral sides during flexion-extension of the knee.

O'Connor model [3] of the tibio-femoral joint is based on the relationship between the geometry of the cruciate ligaments and the geometry of the articular surfaces. It is assumed that the ligaments are straight inextensible line elements attached to the bones, each one at a single point and have no strength in bending. Since the movements allowed to the bones at the human knee occur mainly in the sagittal plane it is adequate to identify the knee as a two-dimensional single degree of freedom linkage.
The cruciate ligaments are represented as two inextensible fibres which, together with the femur and the tibia, are analysed as a crossed four-bar linkage. The ligaments together with the two bones form the "cruciate" linkage ABCD (see Figure *3*). DA is called the tibial link, the line joining the attachment points of the two ligaments to the tibia and it is considered the fixed bar of the knee mechanism. BC is the femoral link. The lengths AB, BC, CD, DA, are called the "parameters" of the linkage. As the knee flexes, the angles between each of the ligaments and each of the bones change. The anterior cruciate tilts towards the tibia and away from the femur with increasing flexion, at the same time the posterior cruciate tilts away from the tibia and towards the femur.

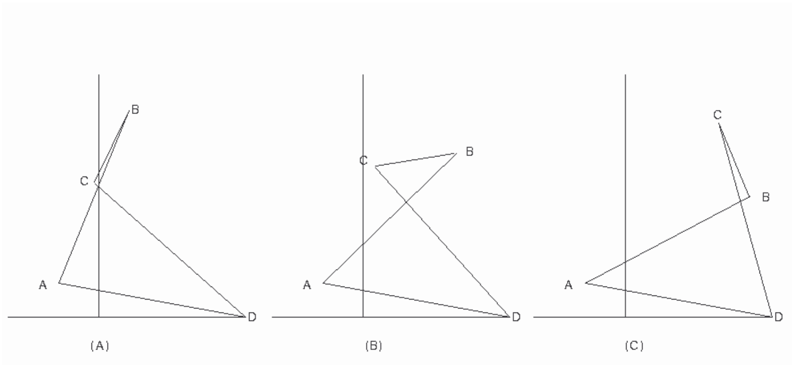

Figure 3: The cruciate linkage at full extension, 70º and 140º of flexion

An important property of the cruciate linkage, on which much geometric and mechanical theory depends, is that the point at which the ligaments cross is the instant centre of rotation (ICR) of the knee joint. Therefore, it is possible to obtain the ICR displacement of the knee, by knowing the motion performed by the four-bar linkage.

3.2. Genetics algorithm methodology

The knee joint will be designed by means of Genetic Algorithms [4] as optimization method. Genetic algorithms are very useful in some optimization problems, in which the functions cannot be written in terms of a mathematical expression and are difficult or impossible to differentiate. These kinds of expressions are not able to be easily solved by analytic optimization.

The standard genetic algorithm proceeds as follows: an initial population of individuals is generated at random or heuristically, and then the population evolves. At every evolutionary step, known as 'generation', the individuals are decoded and evaluated according to some predefined quality criterion or fitness function. To form a new population (the next generation), individuals are selected according to their fitness. Many selection procedures are currently in use, one of the simplest being Holland's [5] original fitness-proportionate selection, where individuals are selected with a probability proportional to their relative fitness. This ensures that the expected number of times an individual is chosen is approximately proportional to its relative performance in the population. Thus, high-fitness individuals stand a better chance of "reproducing", while low-fitness ones are more likely to disappear.

Selection alone cannot introduce any new individuals into the population, i.e., it cannot find new points in the search space. These are generated by genetically-inspired operators, of which the most well known are crossover and mutation. Crossover is performed with probability cross between two selected individuals, called parents, by exchanging parts of their genomes (i.e., encodings) to form two new individuals, called offspring. This operator tends to enable the evolutionary process to move toward "promising" regions of the search space. The mutation operator is introduced to prevent premature convergence to local optima by randomly sampling new points in the search space. It is carried out by flipping bits at random, with some (small) mutation probability. Genetic algorithms are stochastic iterative processes that are not guaranteed to converge; the termination condition may be specified as some fixed maximal number of generations or as the attainment of an acceptable fitness level. Figure 4 presents the standard genetic algorithm proceeding.

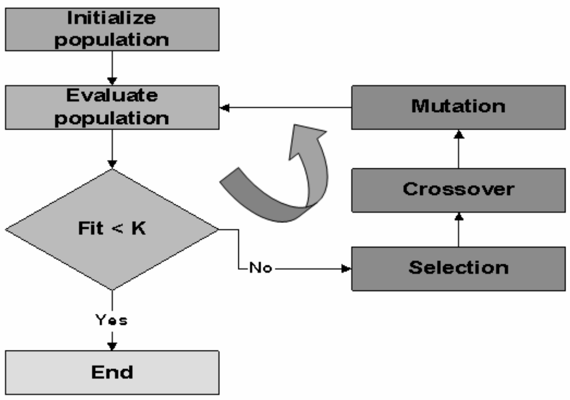

Figure 4: Genetic algorithm proceeding

The genetic algorithms have been programmed under Matlab 6.7. environment. This program makes possible to modify: the crossover probability, the mutation probability and the population size. Several calculations had to be performed to fit these parameters in order to speed up the convergence to the optimal solution of the problem.

The human knee motion calculated with O'Connor and Kurosawa model has been used as input parameter and the coordinates of the four apexes of the four-bar linkage have been used as variable parameters. Before starting with the optimization process, a few restrains have been implemented in order to keep the variable parameters as the coordinates of a four-bar linkage.

- The segments AB, BC, CD and DA are considered to be rigid bodies. The segment AD is contemplated as the fixed bar of the four-bar linkage.
- The range of motion of the four-bar mechanism should be limited, to avoid a possible undetermined solution, depending on the length of the bars. Charts A and B of the Figure *3* show the maximum position allowed by the four-bar mechanism.
- It was assumed that the orthotic knee joint could not be larger than the human knee, to prevent a bulky solution.

In order to minimise variability to reduce the size of the required population and the time of convergence, the numeric representation per gene was scaled linearly between the maximum and the minimum possible values per each variable.

4. Results

It has been obtained more than 10 solutions for the optimal four-bar linkage. These solutions were very similar between them and it has been selected the solution with better fitting to the natural movement of the knee. Figure *5* shows the graphical comparison of the natural knee displacement, obtained from Kurosawa and Walter model, and the displacement performed by several orthotic joints commonly used by patient with different pathologies.
It is possible to observe that the optimal four-bar joint, obtained by means of genetic algorithms (red line), follows more accurately than the others the human knee movement according to the Kurosawa model (yellow line). The maximum difference between both movements is lower than 0.8 mm in the whole range of knee flexion from 0º to 120º. This issue provides the follow advantages:

- **Safety**: Ligament protection. The optimal joint avoids the generation of unwanted forces at the knee level, providing internal soft tissue protection.
- **Comfort**: The kinematics compatibility avoids the relative movement between the orthosis and the lower leg, therefore a better comfort is supplied by this knee joint.

The adaptability is other advantage of the optimal knee joint, because it can be easily customized to each patient by using the genetic algorithm methodology.

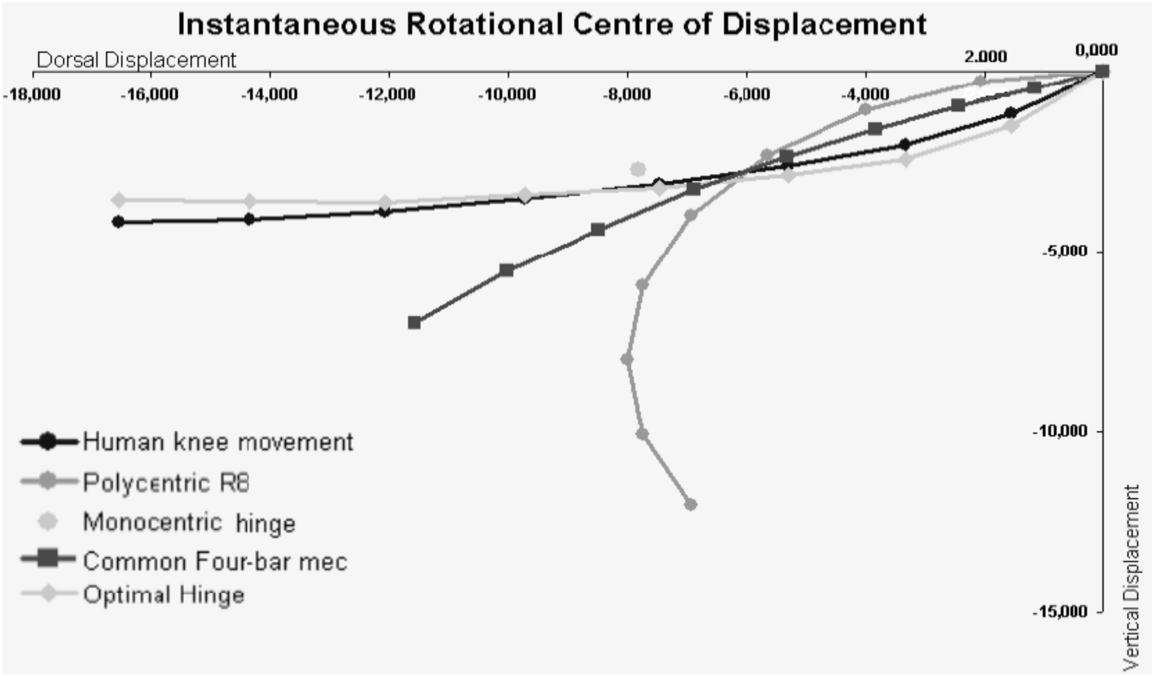

Figure 5: Comparison between orthotic knee joints

5. Conclusions

Genetic algorithms are a suitable mathematical tool for developing knee joints and other kinds of orthotic components which require optimal fitting with the movement of the natural joint. Furthermore, Genetic algorithms could be useful to develop a new concept of customized knee joints, revolutioning the procedure of design of functional orthosis.

The development of optimal and customized joints will enable people with mobility problems at the lower limb, to achieve more comfortable orthotic devices. Computer methods in biomechanics and biomedical engineering can contribute, in this way, to an improvement in their quality of life.

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