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Synthesis for a Knee Rehabilitation Mechanism Applying Genetic Algorithms

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Abstract

This article presents the synthesis of a Slider-crank mechanism, as an instrument for the rehabilitation of knees produced by different types of injuries. According to the physical activities performed by the users, atrophy of muscle groups around the knee is generated. The development of the proposed mechanism involved the biomechanical analysis of movements developed by health professionals during a rehabilitation session. This analysis was carried out through software based on digital image processing, obtaining the points of objective trajectory that the mechanism should imitate. Subsequently, a set of optimal solutions was obtained, applying the technique of genetic algorithms. The solutions obtained allow the designer to take into account factors such as the mechanism's developed trajectory quality, as well as its size. They even allow you to select the degree of importance according to your requirements.

Keywords: Mechanisms Synthesis, Rehabilitation, Genetic Algorithms

INTRODUCTION

Knee injuries are one of the most common conditions in athletes and people with health problems, which can have different types of injuries with different types of therapies and rehabilitation times, commonly they can be contagious. These present muscular atrophy in the extensor muscle groups (quadriceps) and the flexor muscle groups (hamstring, goose foot, popliteus muscle, gastrocnemius, fascia lata), which make the flexion-extension movement of the knee possible [1, 2].

The protocol to follow in the rehabilitation of mobility and muscle strength after a knee injury is to perform a series of repetitive exercises that gradually help the joint recover, this is measured by muscle strength and mobility arcs that occur in the knee. These movements of flexion-extension can be divided into three [3], the passive movement which is performed by the therapist without any intervention from patient [4], the free active movement which the patient performs without any type of load or contrary force to the movement and active resistive movement which the patient performs with load or force contrary to movement [5].

Since the therapist cannot guarantee that the range of mobility and force applied, either by himself or the patient must still go through an equal number of repetitions for each of the movements described, this can generate delays in rehabilitation times or can even affect the joint and muscles that you want to rehabilitate negatively, for this the inclusion of machines and prototypes is important to help make these repetitive movements improve intervention in knee rehabilitation.

Machines that are mostly responsible for continuous passive movement can be purchased, these are used in different health institutions dedicated to rehabilitation and in research centers for their development, the concept of this type of devices was introduced in the 1970s, where it was expected that the main objective of these devices was to reduce spasticity [4], [6-9].

In this paper, we propose the synthesis of a mechanism that allows components to be replicated by a physiotherapist. These movements correspond to muscle groups rehabilitation exercises around the knee. In the following sections: movements' study is described by implementing digital image processing software, selected mechanism's structure, genetic algorithms technique for the links' dimensions and optimal calculation, results and conclusions.

MATERIALS AND METHODS

Target Trajectory's Study and Definition

A study of the knee's joint trajectory was made during flexion-extension movements, taking a linear trajectory with an inclination to better adjust the mechanism to the knee with the greatest precision in the knee's movement [10, 11].

To analyze the trajectory of the two joints, the Kinovea software was used, in the first instance some videos were taken where a physiotherapist performed the flexion-extension movements to a patient in order to extract data that could be used in the trajectory analysis. A video was taken that contained the best visual information so that the movements' study was the most appropriate. In this video the patient had three yellow and triangular marks (see Fig. 1), which were distributed in the most relevant biomechanical areas of the lower extremities which are the hip, knee and ankle.

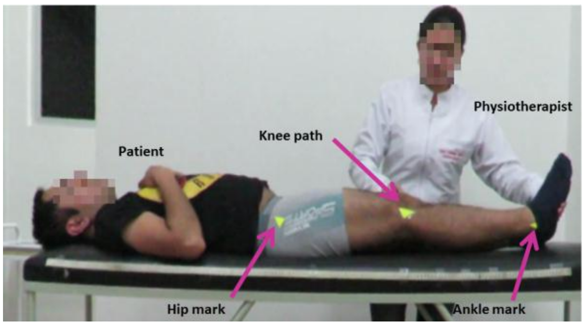


Figure 1. Marks on the patient used to analyze the path developed by the knee.

The first thing that is done is video's the adjustment to length units (centimeters) to obtain data that could be exported and graphed for its identification. This is done by a measuring tape placed on the stretcher's side where the patient is, the position of itself is not relevant as neither is the length of the measuring tap which in this case is 150 cm, using a platform's tool called Line, the tape is marked and the value of it is given to the software. In addition to this, a point that originates coordinates must be placed, which in this case will be the ankle mark in the patient, approximately 10 flexion-extensions were performed and these yielded the results of knee movement.

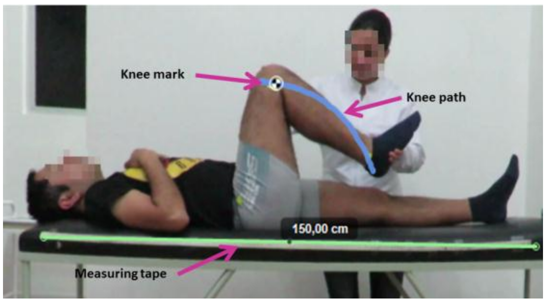


Figure 2. Path developed by the knee.

Mechanism's Kinematic Description

In order to reproduce movements similar to those made by the physiotherapist, the use of a mechanism called a crank, sliding rod (Slider-crank mechanism) was proposed. In Figure 3 you can see the mechanism and the nomenclature used for its dimensions. This mechanism is basically composed of two links (a crank of size L_1 and a connecting rod of size L_2) and a slide inclined an angle α respecting the horizontal. In this mechanism 4 points stand out, $\boldsymbol{P}_0$: corresponds to the axis of rotation of the crank, $\boldsymbol{P}_1$: the joint that connects the two links, $\boldsymbol{P}_2$: it is the slide's point of displacement and in turn is the point on which the user's ankle rest. User's ankle, $\boldsymbol{P}_t$: is the point coinciding with the user's knee [10, 12].

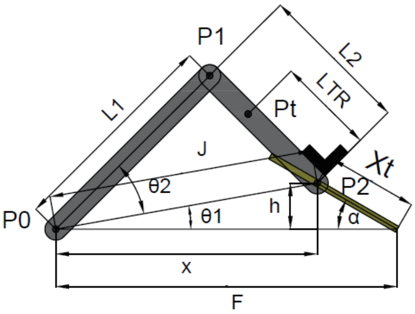


Figure 3. Slider-crank mechanism

In general terms the mechanism constraints must meet the goal that when moving the patient's ankle ($\boldsymbol{P}_2$) through the slide, the knee ($\boldsymbol{P}_t$) should perform a trajectory similar to the movement stipulated by the physiotherapist (described in section 2.1). These restrictions will make the orientation of link 2 (connecting rod) coincide with that of the patient's tibia, given that the patient's leg will be attached to this link. Taking into account these restrictions, mechanism's kinematics where the entry data is the position of the ankle ($\boldsymbol{P}_2$) on the slide (distance X_t) and the output data is the point $\boldsymbol{P}_t$ equivalent to the patient's knee position. The calculations corresponding to this kinematics are described below [11].

Firstly, it must be taken into account that when the mechanism is in the initial position ($\boldsymbol{P}_2$ at the right end of the slide), the patient's leg will be on the table, so the point $\boldsymbol{P}_t$ must be on the same place. From this consideration we can deduce the equation (1)

$$L_1 + L_2 = F \tag{1}$$

Taking the right end of the slide as the coordinate's origin system and knowing that the slide's axis has a slope of an α angle the ankle's distance ($\boldsymbol{P}_t$) with respecting the initial point is X_t, the position of $\boldsymbol{P}_2$ it can be defined as:

$$\boldsymbol{P}_2 = \begin{bmatrix} -X_t \,.\, \cos\alpha \\ X_t \,.\, \sin\alpha \end{bmatrix} \tag{2}$$

From (2) the values of h and x can be deduced as:

$$h = X_t \,.\sin\alpha \tag{3}$$

$$x = F - X_t \,.\cos\alpha \tag{4}$$

Taking the results of equations (3) and (4) is the angle θ_1 corresponding to:

$$\theta_1 = \tan^{-1}\left(\frac{h}{x}\right) \tag{5}$$

Subsequently, the distance J can be calculated as the hypotenuse between the variables found in equations (3) and (4).

$$J = \sqrt{x^2 + h^2} \tag{6}$$

Applying the law of cosines, the angle θ_2 can relate with the mechanism's lengths of L_1, L_2 and the distance J found in the equation (6), obtaining (7).

$$L_2{}^2 = L_1{}^2 + J^2 - L_1\ J\ \cos\theta_2 \tag{7}$$

The equation (7) is cleared and θ_2 can be found.

$$\theta_2 = \cos^{-1}\left(\frac{{L_1}^2+J^2-{L_2}^2}{2\ L_1\ J}\right) \tag{8}$$

When adding the angles θ_1 and θ_2 is the angle that the link L_1 must have with respect to the horizontal called θ.

The points $\boldsymbol{P}_0$ and $\boldsymbol{P}_1$ can be done by means of equations (9) and (10).

$$\boldsymbol{P}_0 = \begin{bmatrix} -F \\ 0 \end{bmatrix} \tag{9}$$

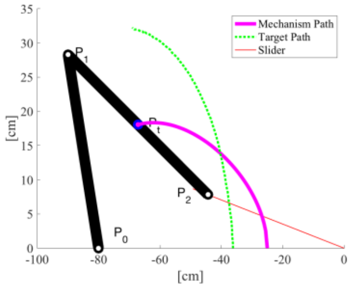
$$\boldsymbol{P}_1 = \boldsymbol{P}_0 + \begin{bmatrix} L_1\ \cos\theta \\ L_1 \sin\theta \end{bmatrix} \tag{10}$$

If $\boldsymbol{P}_{12}$ is the vector that starts from $\boldsymbol{P}_1$ to $\boldsymbol{P}_2$, see (11) and L_{TR} is defined as the constant distance between the patient's ankle and knee, the position of $\boldsymbol{P}_t$ can be calculated according to (12).

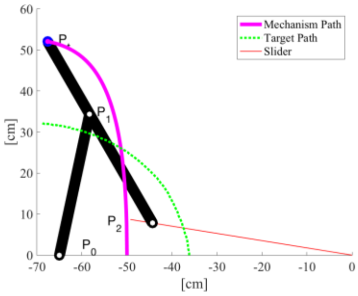
$$\boldsymbol{P}_{12} = \boldsymbol{P}_2 - \boldsymbol{P}_1 \tag{11}$$

$$\boldsymbol{P}_t = \boldsymbol{P}_1 + (L_2 - L_{TR})\ \frac{\boldsymbol{P}_{12}}{\|\boldsymbol{P}_{12}\|} \tag{12}$$

With the mechanism's kinematic equations, it is possible to calculate the trajectory developed by the $\boldsymbol{P}_t$, given the evolution of the slide's positions (X_t). In figure 4 two examples are observed applying different dimensions to the mechanism. In figure 4a the distance in L_{TR} is minor than L_2 and in figure 4b the distance in L_{TR} greater than L_2. The magenta line describes the trajectory made by the mechanisms, while the green line is the objective trajectory, which was obtained in section 2.1. With these calculations we proceed to find the mechanism's ideal dimensions so that the two trajectories are very similar, for the technique of genetic algorithms described in the following section.



a) L_1: 30cm L_2: 50cm L_{TR}: 25cm (P_e: 89.03)



b) L_1: 35cm L_2: 30cm L_{TR}: 59cm (P_e: 168.38)

Figure 4. Paths developed by two mechanisms with different dimensions

Application of Genetic Algorithms for the Mechanism's Synthesis

The application of genetic algorithms can be classified or identified by phases which are: *coding of the problem*, this phase consists in taking the data to a binary representation; initialization, here the random generation of the initial population that is comprised by a set of chromosomes that represent possible problem solutions is carried out; *evaluation*, to each of the chromosomes will be applied a fitness function or fitness equation to compare between them which is the best solution, taking into account that this function is usually maximum / minimum because you want to achieve an optimization; *selection and generation of new population*, after evaluating each chromosome with the fitness function and using its results a new population is generated using the chromosomes with higher qualification, this is done by two ways (see Fig. 5) one that is **recombination** or **crossing** which is done by randomly mixing chromosomes' elements with better fitness scores, or can also be performed by mutation which makes a random change in the chromosomes to contribute to process diversification, after this, these new chromosomes are carried to the evaluation phase to keep evolving. The genetic algorithm's termination conditions are established when there are no major variations in the population [13].

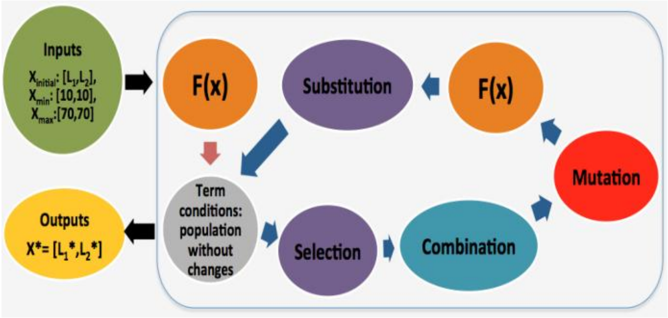


Figure 5. Synthesis of the mechanism path using genetic algorithms.

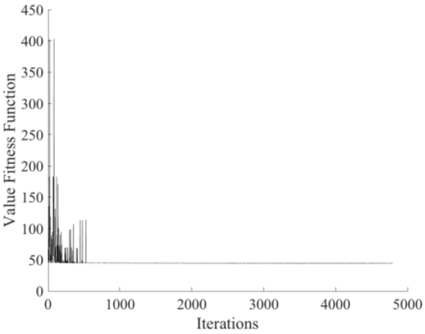
For the genetic algorithms application in the mechanism's synthesis, fitness functions were used to calculate the error between the trajectories defined, see (13). This error corresponds to the sum of the distances between the points developed in the objective trajectory and the mechanism's trajectory for the slide's vectors position, corresponding to the position of the patient's ankle. When this fitness function is minimized, the optimal mechanism's dimensions have been found (L_1*, L_2*).

$$F(x) = E_P = \sum_{i=1}^{n} \left\| \boldsymbol{P}_{t\,target}(X_{ti}) - \boldsymbol{P}_t(X_{ti}) \right\| \tag{13}$$

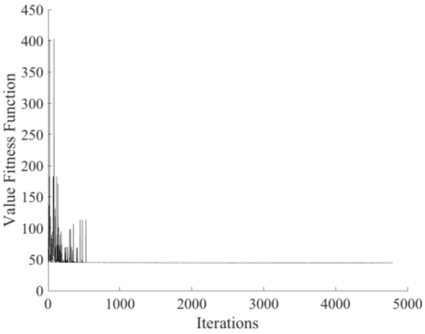
When implementing the genetic algorithms the links' minimum and maximum values were considered as L_1, L_2 (10 – 70 cm) and a constant length of L_{TR} (36.19 cm).

RESULTS

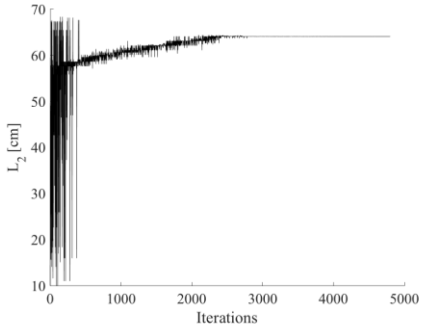
Figure 6 shows the results obtained by minimizing equation (13) by applying the technique of genetic algorithms. Figure 6a shows the evolution of the values obtained by the fitness function over the algorithm's iterations. In this experiment, a value of 44.4238 was obtained for the fitness function, which corresponds to the dimensions of 70cm and 64.07cm for L_1 and L_2 respectively. In figures 6a and 6b its evolution can be seen.



a) Performance of the value obtained from the fitness function throughout the iterations



b) Performance of L_1 throughout the iterations



c) Performance of L_2 throughout the iterations

Figure 6. Application of genetic algorithms in the mechanism synthesis, where the target is the minimum error between paths

Since the target trajectory is composed of 69 points and the value of the fitness function is 44.4238, it can be deduced that the mechanism's average trajectory error is 0.6438cm, which is relatively small. Therefore, the mechanism meets the proposed expectations. However, when analyzing the mechanism's dimensions links, it can be seen that they are relatively large.

In order to calculate a mechanism that has smaller dimensions without neglecting its main objective, 6 cases of fitness functions were proposed. The first corresponds to the previously mentioned case where it is intended to minimize the error between trajectories. In the second case, dimensions of the two links were added to the objective equation so that the objective's value function increased to 115.4303. Since the equations are different, to compare them, the values of E_p, are analyzed, in this case increase to 55.96, however the links' dimensions decreased to L_1: 27.5037 and L_2: 31.9579.

To take into account a factor of importance between the error in the trajectories and the mechanism's links dimensions, an objective function was generated to normalize the characteristics and include two weighting coefficients as described in equation (14).

$$F(x) = a\left(\frac{E_P - minE_P}{maxE_P - minE_P}\right) + b\left(\frac{L_1 + L_1 - minL_1 - minL_1}{maxL_1 + maxL_2}\right) \quad (14)$$

Where:

a: Trajectory error pondering coefficient.

b: Mechanism's dimensions pondering coefficient.

E_P: Error between the objective trajectory and mechanism path.

$minE_P$ y $maxE_P$: Minimum and maximum error between paths.

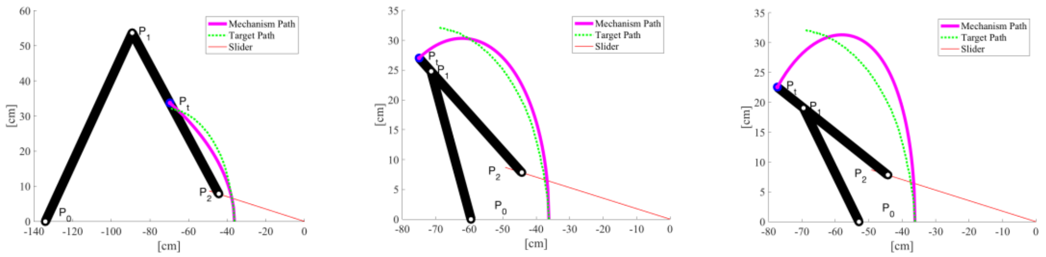
$minL\ y\ maxL$: Minimum and maximum links' permitted dimensions.

By means of equation (14) the cases' fitness functions were proposed: 3 to 6 where the pondering factor between the importance of tracking the path varies between: 50%, 80%, 90% and 95% and the factor corresponding to mechanism's dimensions varies between: 50%, 20%, 10% and 5% respectively. In Table 1, we can see the results obtained from the final value of each fitness function, as well as from the E_P and the lengths of links L_1 and L_2.

Table 1. Results obtained for the 6 cases of fitness functions.

Case	Fitness Function (GA)	L1	L2	Final Fitness Function Value	Path Error (E_P)
1	E_P	70.0000	64.0727	44.4238	44.4238
2	$E_P + L_1 + L_2$	27.5037	31.9579	115.4303	55.9687
3	$0.5(E_P-50)/350+0.5(L_1 + L_2 - 20)/(140)$	25.3010	27.6447	0.1604	65.6725
4	$0.8(E_P-50)/350+0.2(L_1 + L_2 - 20)/(140)$	29.8737	35.6181	0.0957	51.5136
5	$0.9(E_P-50)/350+0.1(L_1 + L_2 - 20)/(140)$	34.0154	40.6900	0.0636	48.1779
6	$0.95(E_P-50)/350 + 0.05(L_1+L_2-20)/(140)$	39.4892	45.9540	0.0437	46.4151

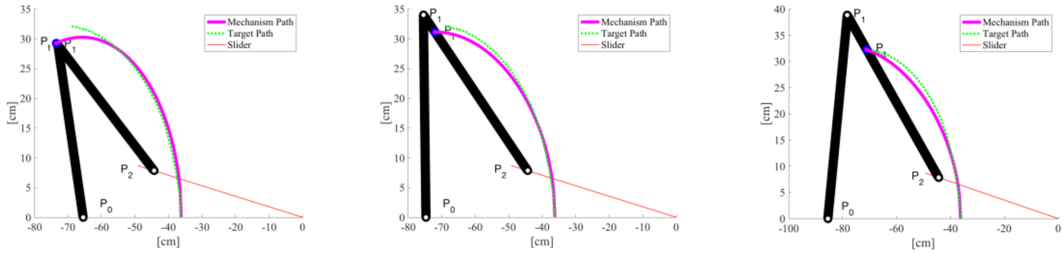
Note that cases 1 and 6 had the best results respecting E_p, however there is a significant difference in the links' dimensions. This allows the designer to decide whether he wants a large mechanism with enough precision or a small mechanism with a slightly larger error. Figure 7 shows the mechanisms obtained and the trajectories developed by them. This figure allows to graphically evaluate paths performance executed by the different mechanisms.



a) Path error (L1: 70cm, L2: 64.07cm, EP: 44.42)

b) Path error + Dimensions (L1: 27.5cm, L2: 31.96cm, EP: 55.97)

c) 50% Path Error and 50% Dimensions (L1: 25.3cm, L2: 27.64cm, EP: 65.67)



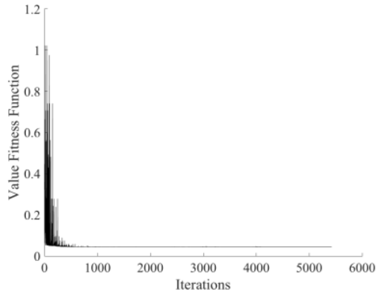
d) 80% Path Error and 20% Dimensions (L1: 29.87cm, L2: 35.61cm, EP: 51.51)

e) 90% Path Error and 10% Dimensions (L1: 34.02cm, L2: 40.49cm, EP: 48.18)

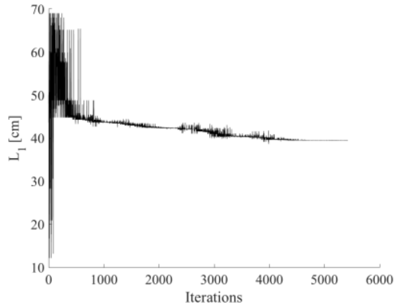
f) 95% Path Error and 0.5% Dimensions (L1: 39.49cm, L2: 45.95cm, EP: 46.42)

Figure 7. Mechanism's synthesis results according to the functions to be minimized

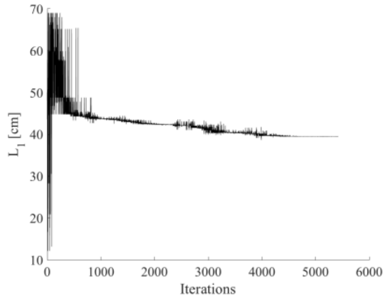
Of the six cases proposed, 1, 5 and 6 show quite interesting results. Case 1 has the best results in terms of path tracking, however its dimensions are relatively large. Cases 5 and 6 correspond to fitness functions where dimension importance is taken in 10% and 5% correspondingly. Therefore in these two cases the dimensions decrease significantly. For case 5 the obtained dimensions were L_1: 34.02cm, L_2: 40.49cm and the error between trajectories (E_P) was 48.18. For case 6 the dimensions were L_1: 39.49cm, L_2: 46.42cm and the error between paths of 46.42. With these results, case 6 can be taken as a good option since it has a smaller size and a good follow-up. In fact, the average value of position error for each point is 0.67cm, only 0.03cm more than for case 1. Figure 8 shows the evolution of the target and the dimensions when applying the genetic algorithms.



a) Performance of the value obtained from the fitness function throughout the iterations



b) Performance of L_1 throughout the iterations



c) Performance of L_2 throughout the iterations

Figure 8. Application of genetic algorithms in the mechanism synthesis, where the target is: the minimum error between paths plus the dimensions with a weighting of 95% and 5% respectly. (L_1: 39.49cm, L_2: 45.95cm, E_P: 46.42)

CONCLUSIONS

The mechanism's synthesis showed that it is possible to obtain devices that replicate with good approximation the movements made by a physiotherapist for knee rehabilitation. These devices will allow a more exhaustive monitoring of patient's evolution and control with greater precision variables such as: the maximum range of movement, speed among others.

The genetic algorithms proved to be a very useful tool for the mechanism's calculation of dimensions, given that an infinite number of possibilities could obtain optimal dimensions according to the designer's criteria, within which follow-up's quality is highlighted for the proposed trajectory and mechanism's size. The latter refers to the fact that a smaller mechanism that fulfills its function in a very approximate way can be obtained. The size's reduction implies an increase of only 0.03cm of average error for each one of the trajectory points.

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