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Design of a Human Knee Reeducation Mechanism

Allaoua BRAHMIA[1], Ridha KELAIAIA[2]

[1] Faculté de Technologie, Université 20 Aout 1955, Skikda, Algerie,
e-mail: a.brahmia@univ-skikda.dz
[2] Faculté de Technologie, Université 20 Aout 1955, Skikda, Algerie,
e-mail: r.kelaiaia@univ-skikda.dz

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Abstract: To establish an exercise in open muscular chain rehabilitation (OMC), it is necessary to choose the type of kinematic chain of the mechanical / biomechanical system that constitutes the lower limbs in interaction with the robotic device. Indeed, it's accepted in biomechanics that a rehabilitation exercise in OMC of the lower limb is performed with a fixed hip and a free foot. Based on these findings, a kinematic structure of a new machine, named Reeduc-Knee, is proposed, and a mechanical design is carried out. The contribution of this work is not limited to the mechanical design of the Reeduc-Knee system. Indeed, to define the minimum parameterizing defining the configuration of the device relative to an absolute reference, a geometric and kinematic study is presented.

Keywords: Rehabilitation robots, lower limbs, open muscle chain, kinematic chain, model geometric and kinematic.

1. Introduction

During the last decades, scientific research in the field of medical engineering and rehabilitation has led to important advances. Thus, rehabilitation robots have been created in order to help therapists during complex and repetitive tasks [1-3]. The robot then allows the realization of predetermined movements constituting the heart of the physical exercise to be performed. Furthermore, the use of a rehabilitation device following the appearance of the deficit allows rapid recovery of motor function. In addition, locum robotics makes it possible to facilitate notably the realization of daily tasks (demotic, chair lifts, object lifts, etc.) [4]. Moreover, the use of robotic devices has become widespread in the field of sports training. Indeed, the addition of controlled actuators makes it possible to extend the range of movements proposed in order to achieve specific objectives that cannot be achieved by conventional drive machines whose principle is limited to the displacement of a heavy load [5]. Thus, the realization of such devices requires, in addition to the medical expertise necessary for the formalization of needs, varied knowledge from many disciplines such as: robotics, biomechanics, mechatronics, automation, and electronics. Robotics Rehabilitation and training has grown considerably in recent years. Motorized devices have been designed and are generally based on architectures similar to those of the weight machines found in the weight rooms. The definition of reference trajectories, the achievable domain or the consideration of articular biomechanics requires collaborative work between experts in the medical field and the designers of the robotic system. From the point of view of the automatic controller, the objective is to guarantee a safe operation for the user while ensuring the realization of the movements according to the performances desired by the medical profession. The automatic controller then allows the definition of control structures ensuring the stability of the controlled system during movements performed, but also allows to take into account the user's interactions with the rehabilitation device to generate physiologically consistent trajectories.

The objective of this work is therefore the design of a new device for knee rehabilitation. The adopted approach follows a process of several stages: study and definition of the objectives in terms of rehabilitation, design of the mechanical architecture, dimensioning of the actuators, and study of the control part, experimental validation and finally clinical study. Note that this entire process cannot be performed in a single job and, therefore, the last three points will be subject to further study.

2. Kinematic description of the movements of the knee joint

A. Segments and joints of the lower limb

The human body is considered as a set of rigid poly-articulated segments. Thus, the joints each have one or more degrees of freedom and each segment may be associated with a reference frame to position it in space. The analysis of the human movement can, by convention, be realized with respect to three planes of references, also called anatomical planes, which are the sagittal plane, the frontal/coronal plane and the transverse plane, as well as three anatomical axes, which are the sagittal axis, the transverse axis and the longitudinal axis (*Fig. 1*). The lower limb consists of three body segments: the thigh, the leg and the foot.

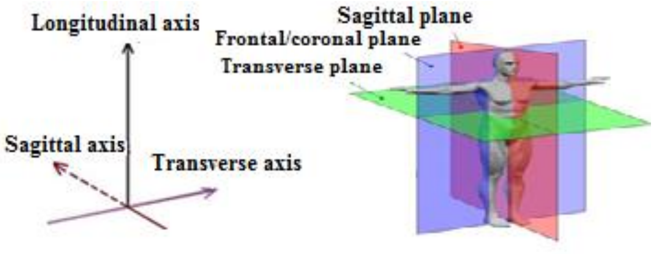

Figure 1: Anatomical planes.

B. The knee joint

The knee is a synovial joint that joins the leg to the thigh, it is located at the lower end of the femur and the upper end of the tibia, it is a joint that supports the weight of the body. It involves three bones, the femur, the tibia and patella (*Fig. 2*), through three joints, the patellofemoral joint the double femoro-tibial joint.

C. Amplitudes of the movements of the knee

The knee is the distal articulation of the thigh. It arouses the interest of the biomechanical community because of its complexity and the multiplicity of its pathologies.

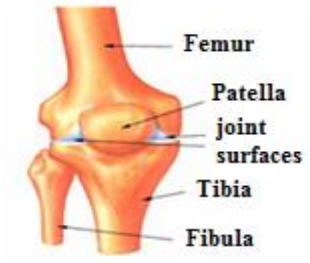

Figure 2: The knee joint [6].

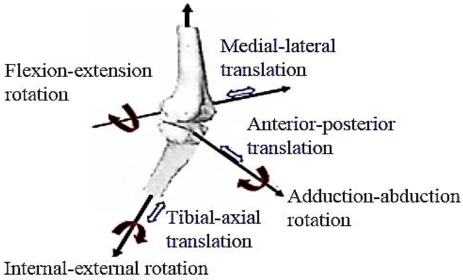

Figure 3: Kinematic description of knee joint movements.

Recent studies have shown that, from an anatomical point of view, the kinematic description of the movements of the knee joint has six axes and six degrees of freedom [7]. These are presented in *Fig. 3*, and consist of three rotations and three translations arranged in a simple kinematic chain [8]. Note that it is commonly accepted that the amplitudes of the translational movements are negligible vis-à-vis the amplitudes of the movements for ordinary tasks (walking, lifting chair). The amplitudes of the flexion-extension movement of the knee vary between 0 ° in hyperextension and 150 ° in hyper-flexion *Fig. 4.a* shows that knee flexion can reach 160 ° when the patient is in a squat position [9]. In addition, the internal and external rotations respectively admit maximum amplitudes of 30 ° and 40 ° (*Fig. 4.b*). Thus, in this work, a single axis of rotation will be considered [10], that is to say: the mediolateral axis around which the flexion-extension takes place.

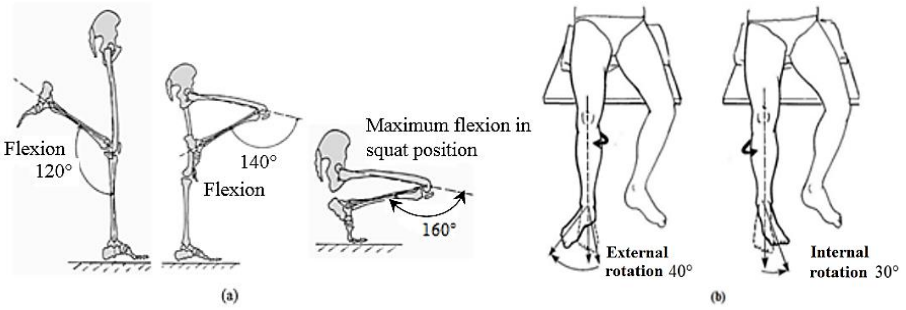

Figure 4: Amplitudes of knee movements.

3. Open Muscular Chain exercises (OMC)

Usually, clinicians commonly accept a definition of OMC exercise: it is an exercise of the lower limbs during which the foot is free during the movement [11]. A knee flexion-extension exercise is performed in an open muscular chain if the dynamic resultant of the force F_d opposing the movement is perpendicular to the longitudinal axis of the leg. *Fig. 5* [12] presents, in a simplified way, the knee flexion and extension movements in OMC.

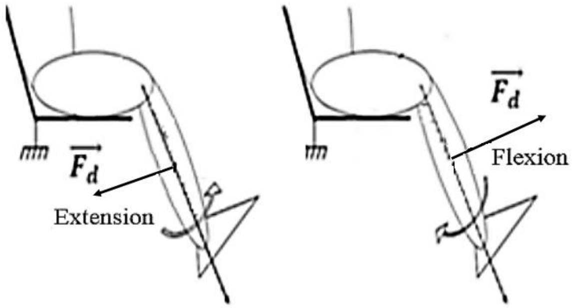

Figure 5: OMC exercises.

4. Concept of the reeducation mechanism “Knee-Reeduc”

The goal of our work is to develop a machine for lower limb rehabilitation to perform open muscle chain exercises. For a device to perform this type of exercise, its kinematic structure must meet certain constraints. By analogy with robotic systems, the mechanical assembly consisting of the lower limbs and the rehabilitation device is a set of polyarticulated rigid segments. Indeed, man is often considered in biomechanics of movement as a poly-articulated and self-controlled mechanical system [13,14].

A. Kinematic concept

For a knee rehabilitation movement to be considered as an exercise in OMC [11], it is possible to consider that the foot must rest on a support. In order to achieve this constraint, the considered choice of the Knee-Reeduc mechanism assumes that the hip is not fixed relative to the frame and that the movement is generated by a mobile support on which the foot rests. In addition, in order to be able to develop a kinematic chain allowing OMC movement to be achieved, the mechanical assembly consisting of the lower limb must form an open kinematic chain, and the rehabilitation device chosen is formed of a closed kinematic chain (*Fig. 6.a* and *Fig. 6.b*). The kinematic design of the new device therefore amounts to defining the nature of L_i links (*Fig. 7*).

L_1 corresponds to the connection between the frame and the segment-thigh. The patient is seated on a seat, which is not fixed to the frame of the machine. The resulting kinematic linkage is a pivot connection corresponding to the coxo-femoral hip joint (connecting the lower limb to the hip). L_2 corresponds to the knee. Let us note that only the movements of the knee along the main axis of flexion extension are sufficient for the kinematic definition of the concept Reeduc-Knee. L_3 represents the connection between the mobile support and the linear module of the machine. This is done by a pivot connection. L_4 corresponds to the connection between the linear module and the frame of the machine. It is characterized by a helical connection along the longitudinal axis defined by the lower limb in full extension. L_5 corresponds to the connection between the moving part of the linear module with the frame. It is characterized by a slider joint.

Fig. 7 shows the kinematic concept used for the knee rehabilitation machine in the sagittal plane. Note that here; the kinematic structure is presented for only one of the two lower limbs. Indeed, the functions of each of the lower limbs are symmetrical.

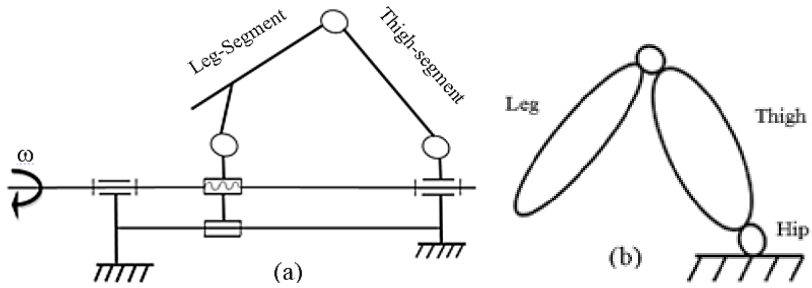

Figure 6: (*a*) Kinematic chain of the rehabilitation device;
(b) Kinematic chain of lower member in OMC.

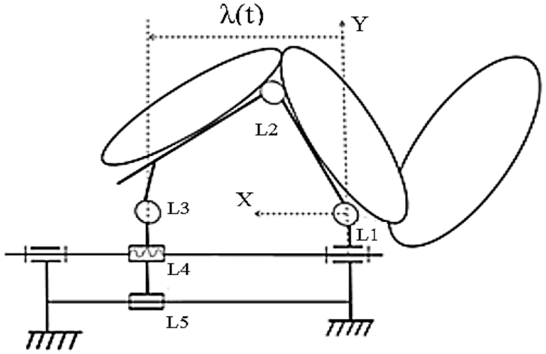

Figure 7: Kinematic concept of Knee-Reeduc in the sagittal plane.

B. Mechanical structure

The design of the mechanical structure of Knee-Reeduc is performed in accordance with the kinematic structure proposed above. Thus, Knee-Reeduc comprises a motorized linear transfer performing the translation L_3. The latter then sets in motion a mobile support (leg-segment and thigh-segment) realizing the rotation L_2 and thus allowing the flexion/extension of the foot. The thigh-segment provides the connection between the leg-segment (pivot link) and the frame through a pivot link L_1. *Fig. 8* shows the type of linear transfers retained to carry out the translation L_5. The moving part of this module is set in motion by the rotation of a transmission screw L_4, the latter being actuated by a reducing motor. The design of this module is carried out for a useful run of 0.8 m to reach a wide panel of users taking into account the maximum length of the lower limb in full extension of a large patient. Finally, the linear module is mounted on a fixed platform (frame). *Fig. 9* shows the mobile support (segment-leg and segment-thigh) made to support the lower limbs. The design of this support is made for a width of 0.25 m. The maximum length of this support including the two segments is equal to 0.95 m (this length is adjustable). *Fig. 10* shows the mechanical part of the Knee-Reeduc machine as a whole.

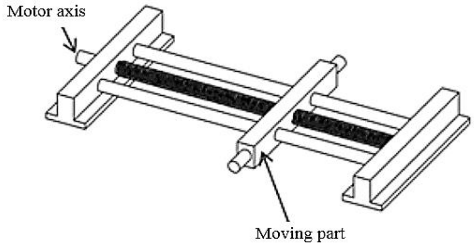

Figure 8: Linear module.

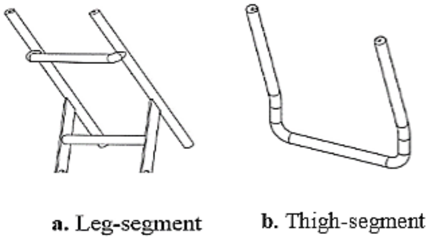

Figure 9: Mobile support.

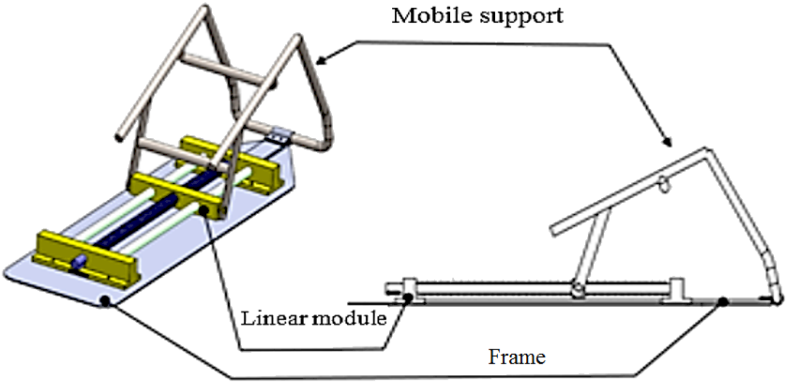

Figure 10: Mechanical part of the machine Knee-Reeduc.

5. Geometric and kinematic modeling of the "Knee-Reeduc" machine

The device is driven by a DC motor, which delivers a constant rotation speed ω (control variable). A nut forming a support is driven by the transmission screw by the speed ω, which makes it possible to move the nut by a translation speed VB (configuration variable or operational variable). The therapist needs to know the value of the flexion of the knee α (the output) at each position λ (the entrance), for that, we have to find a relation between these quantities according to the constants of the system.

A. Geometric model

For a geometric closure, we have:

$$\overrightarrow{OA} + \overrightarrow{AB} + \overrightarrow{BO} = \vec{0} \tag{1}$$

$$D_2\vec{\imath_1} + D_3\vec{\imath_2} - \lambda\vec{\imath_3} = \vec{0} \tag{2}$$

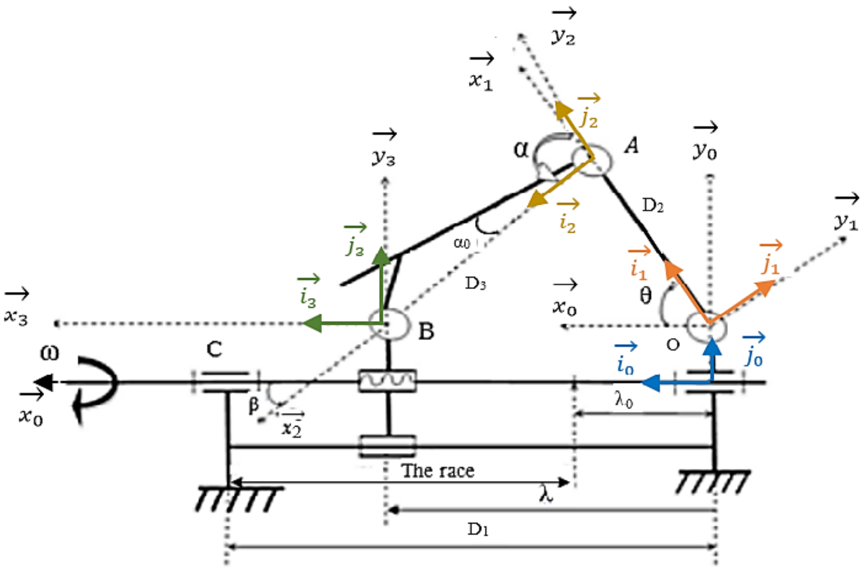

Figure 11: Mechanism of the Knee-Reeduc Device.

In (2), λ is the race ($\lambda_0 \leq \lambda \leq D_1$);
We have:

$$\vec{\imath_1} = \cos\theta\,\vec{\imath_0} + \sin\theta\,\vec{\jmath_0} \tag{3}$$

$$\vec{\imath_2} = \cos\beta\,\vec{\imath_0} - \sin\beta\,\vec{\jmath_0} \tag{4}$$

$$\vec{\imath_3} = \vec{\imath_0} \tag{5}$$

Replace (3), (4) and (5) in (2) we find:

$$(D_2\cos\theta + D_3\cos\ \beta - \lambda)\,\vec{\imath_0} + (D_2\sin\theta -\ D_3\ \ sin\,\beta)\,\vec{\jmath_0} = \vec{0} \tag{6}$$

Therefore, we can find this system

$$\begin{cases} D_2 \cos\theta + D_3 \cos\ \beta - \lambda = 0 \\ D_2 \sin\theta - \ D_3\ \ sin\,\beta\ =\ 0 \end{cases} \tag{7}$$

The system (7) can be written in the form

$$\begin{cases} D_2\ \ cos\,\theta\ + D_3\, cos\,\beta\ =\ \lambda \\ D_2\sqrt{1 - cos^2\theta} - D_3\sqrt{1 - cos^2\beta}\ =\ 0 \end{cases} \tag{8}$$

Putting $\cos\theta = W$ and $\cos\beta = Z$, the system (8) becomes:

$$\begin{cases} D_2 W + D_3 Z = \lambda \\ D_2\sqrt{1 -\ W^2} - D_3\sqrt{1 -\ Z^2} = 0 \end{cases} \tag{9}$$

The resolution of the system (9) can give:

$$\begin{cases} W = \frac{D_2^2 - D_3^2 + \lambda^2}{2D_2\lambda} \\ Z = \frac{\lambda^2 - D_2^2 + D_3^2}{2D_3\lambda} \end{cases} \tag{10}$$

We finally find:

$$\begin{cases} \theta = \text{Arc}\ \cos W \\ \beta = \text{Arc} \cos Z \end{cases} \tag{11}$$

The angular closure allows us to write:

$$\alpha = \theta + \beta \tag{12}$$

α: flexion angle of the knee

Interpretation of the geometric model:

- If the value of λ is minimal ($\lambda = \lambda_0$), we will have a maximum value of α: equivalent to a maximum knee flexion ($\alpha - \alpha_0 = 150$ °).
- If the value of λ is maximal ($\lambda = D_1$), we will have a minimum value of α: equivalent to a minimum knee flexion ($\alpha - \alpha_0 = 0$).

B. Kinematic model

The kinematic model consists of calculating the configuration variable (or operational variable) V_B according to the control variable ω.

We consider that:

$$\varphi = \omega t, \tag{13}$$

where φ represents the angle of rotation of the screw (constant uniform rotation), and t represents the time.

We will have a uniform translation of point B.

If:

$$L_a = V_B \, . \, t, \tag{14}$$

the pitch “S” of the screw corresponds to the unit advance “L_a”

By advancing one turn of the screw, this gives $\varphi = 2\pi$ and $L_a = S$.

Therefore, we get:

$$V_B = \frac{S}{t} \, . \tag{15}$$

For the establishment of the inverse kinematic model, we use the relation between ω and V_B, which is given by:

$$\omega = \frac{2\pi}{S} . V_B \, . \tag{16}$$

To get uniform translation movement, we use the following expression:

$$\lambda = V_B \, . \, t \, . \tag{17}$$

This equation allows us to calculate the value of the race at any moment t. This value is introduced into the system (10) to find the value of knee flexion α at any moment t.

Interpretation of the kinematic model:

The velocity vector of the knee joint is none other than the derivative with respect to the time of the position vector $\overrightarrow{\mathrm{OA}}$.

So:

$$\overrightarrow{\mathrm{V_A}} = \frac{\mathrm{d}}{\mathrm{dt}} (\overrightarrow{\mathrm{OA}}) \tag{18}$$

Therefore:

$$\overrightarrow{V_A} = (\dot{\lambda} + D_3\dot{\beta}\sin\beta)\overrightarrow{x_0} - D_3\dot{\beta}\cos\beta\overrightarrow{y_0} \tag{19}$$

To validate the equations of the geometric and kinematic model, a simulation in Matlab is carried out. *Fig. 12.* shows the different configurations of the Knee-Reeduc for a race of 0.7 m. *Table 1* shows the values of the flexion / extension angles for each position of the Knee-Reeduc, i.e. as a function of the λ stroke, for values of: $D2$ = 0.45 m; $D3$ = 0.4 m; $\alpha_0 \approx 39.5°$.

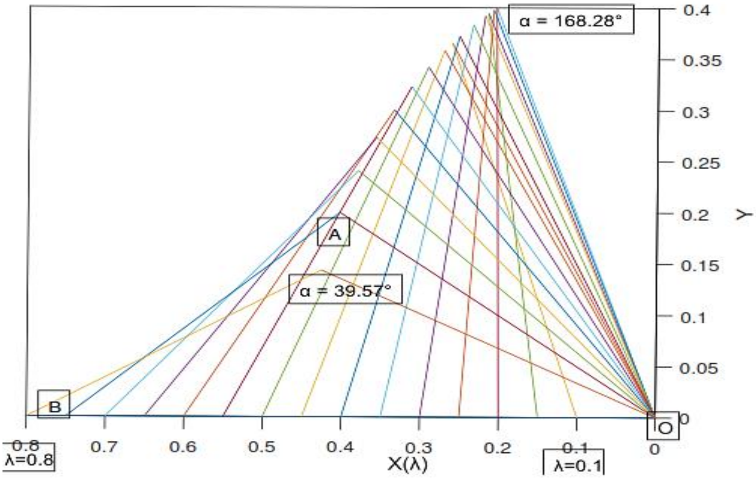

Figure 12: Knee-Reeduc Configuration for $0,1m \leq \lambda \leq 0,8m$.

Table 1: *Values of the flexion / extension angles as a function of the race* λ

The race λ [m]	**flexion / extension angle [°]**
0.1	168.284
0.2	153.615
0.3	139.195
0.4	124.228
0.5	108.200
0.6	90.397
0.7	69.257
0.8	39.571

Thus:

- the maximum flexion of the knee is: $\alpha - \alpha_0$ = 168.284-39.5 = 128.78 °
- the minimum flexion of the knee is: $\alpha - \alpha_0$ = 39.57-39.5 = 0.07 °.

6. Conclusion

In this paper, we have presented a mechanical design of a new human knee reeducation mechanism, named Knee-Reeduc, which is consistent with a fixed hip and a free foot. First we have studied the movements of the knee joint (type, amplitudes, etc.), then we have studied the open muscular chain exercises (OMC), which allowed us to design the mechanical structure of the reeducation mechanism “Knee-Reeduc”. Finally, a geometric and kinematic modeling of the developed mechanism was presented. Taking into account the generic approach followed in this design problem and based on the obtained results, future work concerns the realisation of this machine.

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