Dynamic balancing of RECOVER robotic system

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Abstract. This paper presents a novel robotic system for the lower limb rehabilitation of post-stroke survivors. The model presented in this paper aims to demonstrate an innovative solution that helps in the mobilization of the hip and knee flexion/extension and the ankle plantar flexion/extension and eversion/inversion motions. The paper focuses on achieving the dynamic balancing of the hip-knee module, which due to high accelerations peak values and large size is prone to a certain degree of instability, leading to shaking forces and unwanted vibration that might reduce the safety feelings of the patient. A dynamically balanced mechanism will reduce noise, wear and fatigue and allow higher payload capacity.

1. Introduction

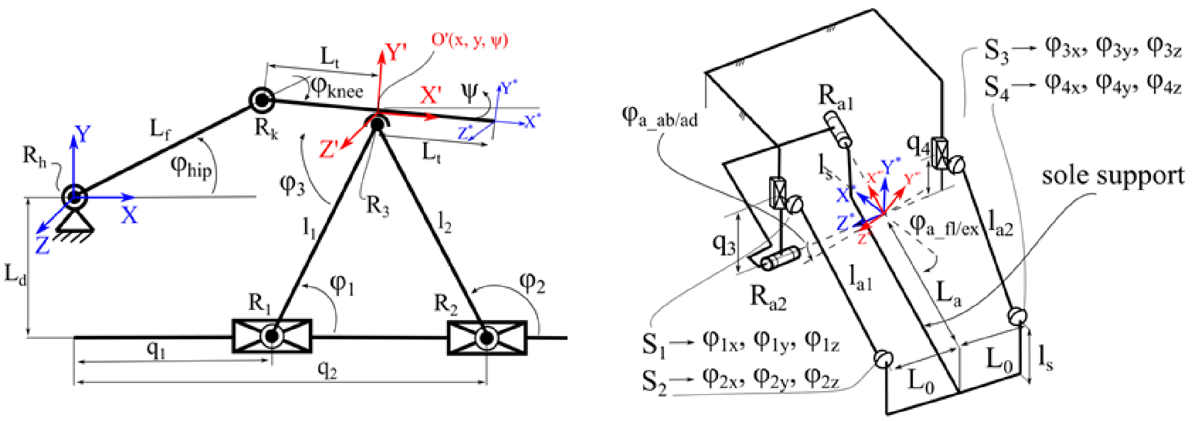
Stroke represents a major cause of disability all over the world, the incidents of stroke increases with the age of the population. For instance, in the United States, 1400.000 people die every year from stroke, while the most majority remain with different grades of permanent disabilities [1]. The principal methods of post-stroke rehabilitation are physical therapy and occupational therapy [2]. These involve the training of repetitive motions by the post stroke survivors having as a target to perform motions of muscles affected by stroke under the strict supervision of qualified medical specialists. The robotic systems can provide advantages like the higher intensity of exercises, the possibility to work simultaneously with more patients, having a precise analysis of the patient rehabilitation progress with an objective evaluation [3].

In last years, more and more the rehabilitation of pathological human gait or of the movements of diseased human joints are using orthotic systems, [4-5] exoskeletons [6], or robotic structures [7-8].

Majority of the robotic systems developed for the lower limb rehabilitation are exoskeletons [9-10], having capacity to sustain the entire body weight. The designs of other robotic systems [11-12] are made for purpose to perform assisted motions of the lower limbs to acquire a higher efficiency while performing rehabilitation exercises, to get a better mobility of patient's and to improve motion coordination and a certain strength of lower limb muscles. There are robotic systems which are dedicated only for ankle joint rehabilitation [13], [14], [15] and parallel structure are suitable for this type of robotic systems. The presented paper aims to show a concept of the RECOVER parallel robotic system and to make an analysis of the dynamic balancing of the hip-knee (HP) module of RECOVER.

2. The kinematic analysis

The aim of RECOVER parallel robot is to perform gait training that involving the motions such as: hip flexion/extension, knee flexion, plantar flexion and dorsiflexion and ankle eversion and inversion. The proposed parallel rehabilitation system is a structure composed of two independent parallel modules, the first module can help in the training motions of hip joint and knee joint, and the second module performs ankle motions. Each module has 2 degrees of freedom with two active joints for both structures [16].



a) b)

Figure 1. Rehabilitation parallel robot (a) kinematic scheme of knee-hip module; (b) kinematic scheme of ankle module [16]

For the hip knee module shown in figure 1 (a) are defined three kinematic chains, the first chain is a RR linkage that is composed from the revolute joints R_h and R_k with free rotation motion for each of them, and the links L_f and L_t. The other two kinematic chains K_{chain1} and K_{chain2} having the same structure PRR type, actuated by q_1 and q_2 respectively. K_{chain1} is composed by R_1 and the link l_1 (with rotation in R_1) and K_{chain2} contain the revolute joint R_2 and the link l_2 (with rotation in R_2). Both K_{chain1} and K_{chain2} intersect in the rotation R_3 [16].

The ankle module presented in figure 1 (b) has also three kinematic chains; the first chain A_{chain0} is an RR linkage having the revolute joints R_{a1} and R_{a2} with orthogonal axis which intersect in the origin of both fixed and moving coordinate frames. The chain supports the patient's sole in the way that the ankle rotation axes should be aligned with the R_{a1}, R_{a2} axes. The distance L_S is adjustable to fit with anthropomorphic variations.

The second and third kinematic chains A_{chain1} and A_{chain2} both are PSS input chains, symmetrically assembled with respect to X^*Y^* plane. For example, A_{chain1} starts with the distance l_0 on Z^* direction ($-L_0$ for the A_{chain2}) and has the link l_{a1} between two spherical joints S_1 and S_2 ,and the link l_{a2} is placed between S_3 and S_4 for A_{chain2}. The spherical joints S_1 and S_3 are attached to the active joints q_3 and q_4 respectively. The spherical joints S_2 and S_4 are both of them attached to the mobile platform (the "T" shape link with L_a and $2\times L_0$ lengths).

3. Dynamic balancing of the Hip-Knee module of the RECOVER robotic system

Gait rehabilitation using the RECOVER [16], [17] robotic system imposes large amplitude motions for the hip-knee module (actuated by the q_1 and q_2 active joints), motions performed in a rather short

time, depending on the rehabilitation status of the patient. This leads to higher linear accelerations (up to 1.6g) [16],[17] which, if the mechanism is out of balance will lead to the appearance of shaking forces and unwanted vibrations, which will negatively affect the rehabilitation process. One way to avoid vibrations may be to apply dumping, but the motions amplitude and the need of reduced noise forbid this kind of approach. Dynamically balanced mechanisms lead to reduced noise, wear and fatigue and an increased payload capacity [18],[19], One way to dynamically balance parallel mechanisms is to use the Linear Independent Vector Method [20] which uses loop equations, but it may be complicated to implement. Another way is to use the principle of linear momentum conservation that lead to a set of conditions that describe a balanced mechanism. It has been proved [21], that when the linear momentum is conserved the parallel mechanism is force balanced and when the angular momentum is conserved the mechanism is moment balanced for any motion of the mechanism. In this paper, the linear momentum equations are computed for each leg initially without using the loop equations and then and loop equations are included and the force balance conditions are obtained, leading to an optimized design for the rehabilitation mechanism.
Figure 2 shows the topology of the RECOVER robotic system, pointing out the mass centers (MC) of each link. The masses m_1 and m_2 contain only the mass of the respective link, while m_3 and m_4 incorporate ale the presumptive mass of the patient's respective limbs - the thigh and the leg (a male of 1.73 m height has been considered) and the weight of the patient's foot as well as the weight of the ankle module. Each MC is defined by two parameters: ai and pi, namely the distances along and respectively perpendicular on the link to which the MC belongs. Applying the linear momentum conservation principle means that the forces acting on the mechanism's links are balanced and the vibrations are reduced to a minimum. Writing the positions of the MCs of each link, it yields:

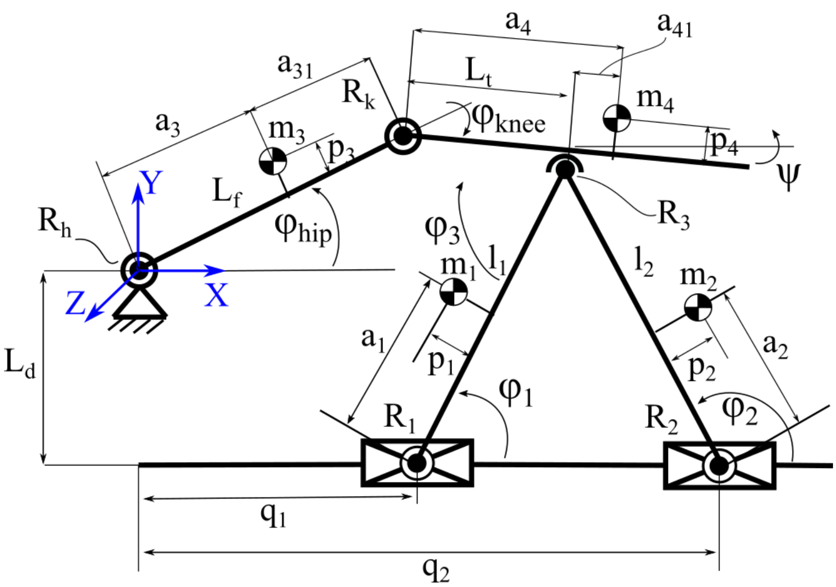


Figure 2. The ***HK module*** of the RECOVER rehabilitation robotic system.

$$r_1 = \begin{bmatrix} q_1 + a_1\cos(\varphi_1) - p_1\sin(\varphi_1) \\ a_1\sin(\varphi_1) + p_1\cos(\varphi_1) \\ 1 \end{bmatrix} \tag{1}$$

$$r_2 = \begin{bmatrix} q_2 + a_2\cos(\varphi_2) - p_2\sin(\varphi_2) \\ a_2\sin(\varphi_2) + p_2\cos(\varphi_2) \\ 1 \end{bmatrix} \tag{2}$$

$$r_3 = \begin{bmatrix} a_3\cos(\varphi_{hip}) - p_3\sin(\varphi_{hip}) \\ L_d + a_3\sin(\varphi_{hip}) + p_3\cos(\varphi_{hip}) \\ 1 \end{bmatrix} \quad (3)$$

$$r_4 = \begin{bmatrix} a_4\cos(\varphi_{hip} - \varphi_{knee}) + p_4\sin(\varphi_{hip} - \varphi_{knee}) \\ L_d + a_4\sin(\varphi_{hip} - \varphi_{knee}) + p_3\cos(\varphi_{hip} - \varphi_{knee}) \\ 1 \end{bmatrix} \quad (4)$$

The linear momentum equations without considering the loop equations are obtained by deriving the equations 1 – 4, which yields:

$$P = \sum_{i=1}^{4} m_i \dot{r}_i = \begin{bmatrix} \delta_{\varphi x1} m_1 \dot{\varphi}_1 + \delta_{\varphi x2} m_2 \dot{\varphi}_2 + \delta_{\varphi x3} m_3 \dot{\varphi}_{hip} + \delta_{\varphi x41} m_4 \dot{\varphi}_{hip} \\ + \delta_{\varphi x42} m_4 \dot{\varphi}_{knee} + m_1 \dot{q}_1 + m_2 \dot{q}_2 \\ \delta_{\varphi y1} m_1 \dot{\varphi}_1 + \delta_{\varphi y2} m_2 \dot{\varphi}_2 + \delta_{\varphi y3} m_3 \dot{\varphi}_{hip} + \delta_{\varphi y41} m_4 \dot{\varphi}_{hip} + \delta_{\varphi y42} m_4 \dot{\varphi}_{knee} \end{bmatrix} \quad (5)$$

Where:

$$\delta_{\varphi xi} = -\left(a_i\cos(\varphi_i) + p_i\sin(\varphi_i)\right),\ i = \overline{1,2} \quad (6)$$

$$\delta_{\varphi x3} = -\left(a_3\sin(\varphi_{hip}) + p_3\cos(\varphi_{hip})\right) \quad (7)$$

$$\delta_{\varphi x41} \equiv -\delta_{\varphi x42} = a_4\sin(\varphi_{knee} - \varphi_{hip}) - p_4\cos(\varphi_{knee} - \varphi_{hip}) \quad (8)$$

$$\delta_{\varphi yi} = a_i\cos(\varphi_i) - p_i\sin(\varphi_i),\ i = \overline{1,2} \quad (9)$$

$$\delta_{\varphi y3} = a_3\cos(\varphi_{hip}) - p_3\sin(\varphi_{hip}) \quad (10)$$

$$\delta_{\varphi y41} \equiv -\delta_{\varphi y42} = a_4\cos(\varphi_{knee} - \varphi_{hip}) + p_4\sin(\varphi_{knee} - \varphi_{hip}) \quad (11)$$

To force balance the robot, the value of P (Eq. 5) should be constant (zero), which further means that all equations Eq. 6 – 11 need to be zero, yielding that $a_i = 0$ and $p_i = 0$, which would concentrate the mass of each link in its origin, namely R_1, R_2, R_h, R_k . A possible topology is presented in figure 3, in which the links L_f, L_t, l_1, l_2 need to have their mass center placed in the rotation joints R_1, R_2, R_h, R_k to obtain the force balance. This solution is trivial and rather easy to implement.

The solutions presented in equations 6 – 11 do not consider the loop equations. There are four independent loop equations which can be written as:

$$r_{3i} = \begin{bmatrix} a_{31}\cos(\pi + \varphi_{hip}) - p_3\sin(\pi + \varphi_{hip}) + (a_4 - a_{41})\cos(\pi - \varphi_{knee} + \varphi_{hip}) + l_i\cos(\varphi_i) + q_i \\ a_{31}\sin(\pi + \varphi_{hip}) + p_3\cos(\pi + \varphi_{hip}) + (a_4 - a_{41})\sin(\pi - \varphi_{knee} + \varphi_{hip}) + l_i\sin(\varphi_i) \end{bmatrix} \quad (12)$$

$$r_{4i} = \begin{bmatrix} a_{41}\cos(\varphi_i - \varphi_{knee} + \varphi_{hip}) - p_4\sin(\varphi_i - \varphi_{knee} + \varphi_{hip}) + l_i\cos(\varphi_i) + q_i \\ a_{41}\sin(\varphi_i - \varphi_{knee} + \varphi_{hip}) + p_4\sin(\varphi_i - \varphi_{knee} + \varphi_{hip}) + l_i\sin(\varphi_i) \end{bmatrix} \quad (13)$$

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where $i=\overline{1,2}$ and the mass parameters a_{31} and a_{41} are indicated in figure 2.

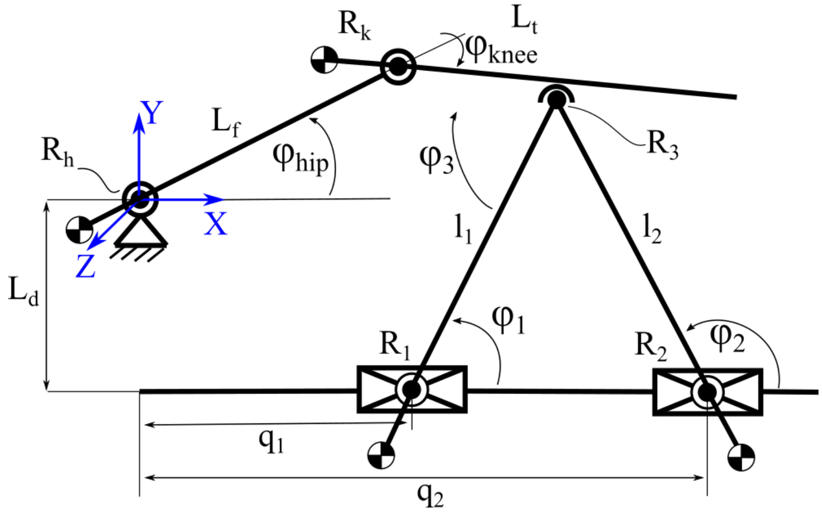

Figure 3. The topology of the force balance solution for the ***HK module*** of the RECOVER robotic system.

The time derivatives of these equations are:

$$\dot{r}_{3i}=\begin{bmatrix} \dot{q}_i-l_i\dot{\varphi}_i\sin(\varphi_i)-\dot{\varphi}_{hip}\begin{pmatrix} a_{31}\sin(\alpha)-p_3\cos(\alpha)+\\ (a_4-a_{41})\sin(\beta)\end{pmatrix}+(a_4-a_{41})\dot{\varphi}_{knee}\sin(\beta)\\ l_i\dot{\varphi}_i\cos(\varphi_i)+\dot{\varphi}_{hip}\begin{pmatrix} a_{31}\cos(\alpha)-p_3\sin(\alpha)+\\ (a_4-a_{41})\cos(\beta)\end{pmatrix}-(a_4-a_{41})\dot{\varphi}_{knee}\cos(\beta)\end{bmatrix} \tag{14}$$

$$\dot{r}_{4i}=\begin{bmatrix} \dot{q}_i-\dot{\varphi}_i\left(a_{41}\sin(\gamma_i)+p_4\cos(\gamma_i)+l_i\sin(\varphi_i)\right)+(\dot{\varphi}_2-\dot{\varphi}_1)\left(a_{41}\sin(\gamma_i)+p_4\cos(\gamma_i)\right)\\ \dot{\varphi}_i\left(a_{41}\cos(\gamma_i)-p_4\sin(\gamma_i)+l_i\cos(\varphi_i)\right)+(\dot{\varphi}_2-\dot{\varphi}_1)\left(a_{41}\sin(\gamma_i)+p_4\cos(\gamma_i)\right)\end{bmatrix} \tag{15}$$

where,

$$\alpha=\pi+\varphi_{hip};\ \beta=\pi-\varphi_{knee}+\varphi_{hip};\ \gamma_i=\varphi_i+\varphi_{hip}-\varphi_{knee},\ i=\overline{1,2}$$

The time derivatives of r_3 and r_4 are:

$$\dot{r}_3=\dot{\varphi}_{hip}\begin{bmatrix} -a_3\sin(\varphi_{hip})-p_3\cos(\varphi_{hip})\\ a_3\cos(\varphi_{hip})-p_3\sin(\varphi_{hip})\end{bmatrix} \tag{16}$$

$$\dot{r}_4=\begin{bmatrix} (\dot{\varphi}_{knee}-\dot{\varphi}_{hip})\left(a_4\sin(\varphi_{knee}-\varphi_{hip})+p_4\cos(\varphi_{knee}-\varphi_{hip})\right)\\ (\dot{\varphi}_{knee}-\dot{\varphi}_{hip})\left(-a_4\cos(\varphi_{hip}-\varphi_{knee})+p_4\cos(\varphi_{hip}-\varphi_{knee})\right)\end{bmatrix} \tag{17}$$

So, the loop equations are:

$$\dot{r}_3=\dot{r}_{3i},\ i=\overline{1,2} \tag{18}$$

$$\dot{r}_4 = \dot{r}_{4i}, i = \overline{1,2} \tag{19}$$

These loop equations can be substituted in the linear momentum equation (equation 5) in several ways. A straightforward way would be to determine φ_i, more precisely $\sin(\varphi_i)$ and $\cos(\varphi_i)$ as well as $\dot{\varphi}_i$ and $\dot{q}_1$. Therefore, the most convenient is to determine $\dot{q}_1$ and $\dot{q}_2$ using equation 14 and equation16 and replace them in equation 5. Thus, the general force balance conditions for the hip/knee module of RECOVER are:

$$\left(-\left(a_1\sin(\varphi_1)+p_1\cos(\varphi_1)\right)m_1 + l_1\sin(\varphi_1)m_1\right)\dot{\varphi}_1 = 0 \tag{20}$$

$$\left(-\left(a_2\sin(\varphi_2)+p_2\cos(\varphi_2)\right)m_2 + l_2\sin(\varphi_2)m_1\right)\dot{\varphi}_2 = 0 \tag{21}$$

$$\begin{gathered}\dot{\varphi}_{hip}\sin(\varphi_{hip})\begin{pmatrix}-m_1a_{31} - m_1(a_4 - a_{41})\cos(\varphi_{knee}) \\ -m_1a_3 - m_2a_{31} - m_2(a_4 - a_{41})\cos(\varphi_{knee})\end{pmatrix} \\ + \dot{\varphi}_{hip}\sin(\varphi_{hip})\begin{pmatrix}-m_2a_3 - m_3a_3 - m_4a_4\cos(\varphi_{knee}) \\ -m_4p_4\sin(\varphi_{knee})\end{pmatrix} = 0\end{gathered} \tag{22}$$

$$\begin{gathered}\dot{\varphi}_{hip}\cos(\varphi_{hip})\begin{pmatrix}-m_1p_3 + m_1(a_4 - a_{41})\sin(\varphi_{knee}) - \\ m_1p_3 - m_2p_3 + m_2(a_4 - a_{41})\sin(\varphi_{knee})\end{pmatrix} \\ + \dot{\varphi}_{hip}\cos(\varphi_{hip})\begin{pmatrix}-m_2p_3 - m_3p_3 + m_4a_4\sin(\varphi_{knee}) \\ -m_4p_4\cos(\varphi_{knee})\end{pmatrix} = 0\end{gathered} \tag{23}$$

$$\dot{\varphi}_{knee}\sin(\varphi_{hip})\begin{pmatrix}m_1(a_4 - a_{41})\cos(\varphi_{knee}) + m_2(a_4 - a_{41})\cos(\varphi_{knee}) + \\ m_4a_4\cos(\varphi_{knee}) + m_4p_4\sin(\varphi_{knee})\end{pmatrix} = 0 \tag{24}$$

$$\dot{\varphi}_{knee}\cos(\varphi_{hip})\begin{pmatrix}-m_1(a_4 - a_{41})\sin(\varphi_{knee}) - m_2(a_4 - a_{41})\sin(\varphi_{knee}) - \\ m_4a_4\sin(\varphi_{knee}) + m_4p_4\sin(\varphi_{knee})\end{pmatrix} = 0 \tag{25}$$

$$\left(a_1\cos(\varphi_1) + p_1\cos(\varphi_1)\right)m_1\dot{\varphi}_1 = 0 \tag{26}$$

$$\left(a_2\cos(\varphi_2) + p_2\cos(\varphi_2)\right)m_2\dot{\varphi}_2 = 0 \tag{27}$$

$$\dot{\varphi}_{hip}\sin(\varphi_{hip})\left(-p_3m_3 + m_4a_4\sin(\varphi_{knee}) - p_4m_4\cos(\varphi_{knee})\right) = 0 \tag{28}$$

$$\dot{\varphi}_{hip}\cos(\varphi_{hip})\left(a_3m_3 + m_4a_4\cos(\varphi_{knee}) + p_4m_4\sin(\varphi_{knee})\right) = 0 \tag{29}$$

$$\dot{\varphi}_{knee}\sin(\varphi_{hip})\left(-m_4a_4\sin(\varphi_{knee}) + p_4m_4\cos(\varphi_{knee})\right) = 0 \tag{30}$$

$$\dot{\varphi}_{knee}\cos(\varphi_{hip})\left(-m_4a_4\cos(\varphi_{knee}) - p_4m_4\sin(\varphi_{knee})\right) = 0 \tag{31}$$

From equations 20, 21, 26 and 27 it yields:

$$a_1 = 0; p_1 = 0; a_2 = 0; p_2 = 0 \tag{32}$$

meaning that the mass center of the links l_1 and l_2 is concentrated in the R_1 and R_2 rotation joints. For the other two links, for the a_3 and a_4 mass parameter there are two possibilities: from equations 22 – 25 it yields:

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$$a_3 = -L_f \frac{m_1 + m_2}{m_3} \text{ and } a_4 = -L_t \frac{m_1 + m_2}{m_4} \tag{33}$$

and from equations 28 – 31 it yields:

$$a_3 = 0 \text{ and } a_4 = 0 \tag{34}$$

while for the mass parameters p_3 and p_4 it yields only one solution:

$$p_3 = 0 \text{ and } p_4 = 0 \tag{35}$$

The resultant topologies yield from equations 33-35, but, from the architectural point of view they are identical (and presented in figure 3), the only difference consisting in the size of the mass parameters. The two resulting solutions would converge in any of these cases: a. $L_f = 0 \text{ and } L_t = 0$ (this is impossible since it would lead to a singular configuration and the robot would fail to accomplish its task); b. $m_1 + m_2 \to 0$ (this is also impossible, but a small mass of these elements is undoubtedly desirable); c. $m_3 \to 0 \text{ and } m_4 \to 0$ (again impossible).

Figure 4 shows a possible design of the RECOVER where the counterweights are mounted on links L_f, L_t, l_1, l_2 such as their mass centers will be concentrated in the rotation joints of each links, namely R_1, R_2, R_h, R_k . Also, in the figure is shown a detailed design of the ankle module. The actuation of the HK module is achieved by two stepper motors and timing belts (q_1 and q_2). The Ankle module is actuated by two smaller size stepper motors using ball screws mechanism (q_4 and q_4).

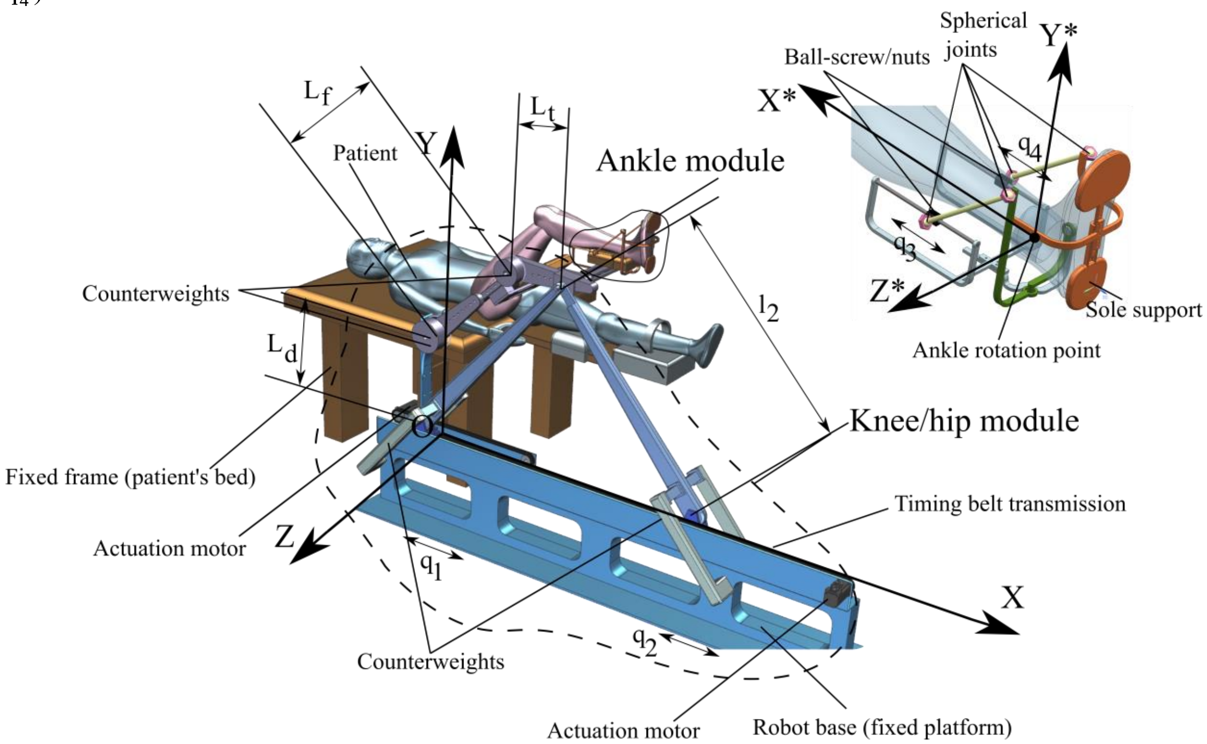

Figure 4. The RECOVER robotic system CAD design.

4. Conclusions

The solution described in this paper comes with the advantage that the patient rehabilitation can start in early stages, when the patient is bedridden, unable to adopt a standing position. RECOVER rehabilitation robot has a hybrid structure having two modules running simultaneously, one to perform motions for hip and knee and the second to offer training motions for ankle joint. The dynamic balancing solution provides a solution for achieving a lightweight structure and keeping the high accelerations and velocities required for gait training, as previously determined, in order to fulfil the design requirements that satisfy the medical protocols. This paper presents also some design considerations of a parallel robotic system for lower limb rehabilitation. Future work will continue with the experimental model of the parallel robot to proof the design inputs.

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