Knee Rehabilitation Device with Soft Actuation: An Approach to the Motion Control

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Abstract: Assistive devices in rehabilitation have gained much attention in robotics research. Recent actuation systems include compliant elements to provide advantages as natural motions and safety in the interaction with humans. These are the so-called soft actuators, among which there are series elastic actuators (SEA) and variable stiffness actuators (VSA). On the other hand, control strategies are required in order to accomplish desired tasks in a proper manner. In rehabilitation systems this is to reproduce a desired motion without affecting the patient, so the control system is crucial. In this paper, we present a control strategy for a knee rehabilitation device, with soft actuation. The goal is to control the system while maintaining the intrinsic softness of the system when the patient is in the rehabilitation process. We propose a feedback control strategy, acting in a defined threshold to maintain the stiffness of the system, combined with a feedforward decision control to reject disturbances.

1 INTRODUCTION

In recent years there has been an increasing need for physical therapy for different reasons. E.g., according to the World' Health Organization[1] near 15% of world's population has some disability caused by accidents, chronic diseases, or other conditions. Besides, people of all ages practice sports frequently to maintain their quality of life, but in this way, they are more exposed to joint injuries.

Any case of impairment or injury requires rehabilitation to reduce pain, to improve or to maintain the remaining functional and structural characteristics of the musculoskeletal system. Rehabilitation includes several practices that aim to recover functions that have been lost or diminished by a disease or accident, though we will specifically refer to physical rehabilitation of the knee (Andrade et al., 2014). According to (Jensen and Lorish, 1994), not all the patients comply with the physical treatments prescribed due to costs, difficulty to reach the physiotherapy's place, and so on. On the other hand, performing the exercises correctly might also be challenging due to the pain, the lack of strength and the lack of range of mobility, not to mention the risks for the physiotherapist when assisting some patients. For these reasons, recent studies aim to contribute to improve the availability and effectiveness of physical therapy, as well as to reduce risks to the physiotherapist, by designing assistive rehabilitation devices. In the last years, devices for upper limb (see e.g. (Balasubramanian et al., 2008) or (Mghames et al., 2017)), and for lower limb rehabilitation have notably increased. Other examples are presented in (Koller-Hodac et al., 2010), (Rifaï et al., 2017) or (Vouga et al., 2017). The requirements are specific, i.e. safety, natural motions. In this sense, the actuation system is a key for robotic devices. Regarding the requirements for rehabilitation, the so-called soft actuators are used in recent developments due to the advantages that they provide (Grioli et al., 2015).

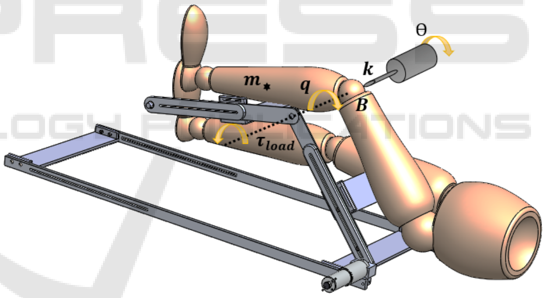

Figure 1: Model representation for knee rehabilitation.

A general concern in robotic devices, and partic-

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[1] http://www.who.int/

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ularly when intended to use in applications that involve interaction with humans, e.g. in rehabilitation, is the control strategy to assure that the system is performing the task with the required specifications, e.g. zero tracking error. Classical control strategies, based on feedback compensation are effective for this purpose, however, they modify the system dynamics. According to (Della-Santina et al., 2017), these strategies may cancel the compliant dynamics, eliminating the desired intrinsic characteristics of soft actuation. In (Della-Santina et al., 2017) authors show that an anticipative model of human motor control, using a feedforward action, combined with low-gain feedback, can be used to achieve human-like behavior in soft actuated devices. Following this idea, we introduce a control strategy that does not cancel the compliant dynamics, based on the combination of feedforward and feedback actions, oriented to control the motion of a soft actuated knee rehabilitation device. In the literature there are other works that tackle problems related to the control of rehabilitation devices. For instance, (Witte et al., 2017), presents a closed loop torque control using classical proportional feedback control with damping injection in conjunction with iterative learning a knee exoskeleton. According to (Grioli et al., 2015) and (Della-Santina et al., 2017) many efforts have been done to control soft actuated systems, as for example PD control strategies (DeLuca and Flacco, 2011), feedback linearization (Petit and Albu-Schffer, 2011), backstepping (Petit et al., 2015) immersion and invariance theories (Wimboeck et al., 2010), optimal control (Ozparpucu and Albu-Schaffer, 2014), and so on.

Regarding rehabilitation devices that use compliant actuation and require a control strategy, some approaches are available. For instance, the control of an assistive orthopedic system for rehabilitation based on inherent compliant actuators has been presented in (Wilkening et al., 2011). In (Mghames et al., 2017) a one degree of freedom assistive platform to augment the strength of upper limbs with VSA is presented. Authors aim to control the system in feedforward by mapping the Electromyographic signals (from muscle activation), to exploit the muscle-like dynamics of the mechanical device. However, a complete analysis of the control problem for the system is left as future work.

Furthermore, a compliant actuated parallel ankle rehabilitation robot is presented in (Jamwal et al., 2016). The robot allows the patients to modify the robot motions according to their own level of disability by applying the strategy of interactive training based on impedance control. This control scheme is dependent on the therapists decision, therefore automatic adaptation between impedance control modes with low and high compliance is required.

In (Romero A. et al., 2017), a 5-bars-linkage underactuated device for knee rehabilitation, using VSA was presented, as shown in Fig.1. A control strategy is required for the latter system, to perform desired routines for knee rehabilitation. To gain an insight of the control strategy and the requirements, we will first consider a one-Degree-of-Freedom (DoF) model. In this way, here we define the control specifications from the patient's point of view, to perform a desired motion during knee rehabilitation therapy. We propose a control strategy for the one DoF soft actuated device, with the aim to maintain the intrinsic dynamic properties of the system in order to exploit its advantages. Results show that the global control strategy proposed which combines feedback and feedforward position control strategy, satisfies the conditions presented in (Della-Santina et al., 2017), allowing maintain the intrinsic softness of the system, while achieving the requirements of the one DoF system, i.e. compensating with the feedforward strategy the disturbances due to the leg's weight, keeping the stability of the system. When approaching the 80% of the reference, we switch the control parameters in order to have a lower velocity near to the reference. In future works, we will study the validity of the control strategy in the 5-bars-linkage-rehabilitation device.

2 DEVICE MODELING APPROACH

This paper tackles an approach to controlling a soft-actuated rehabilitation device - see Fig.1.

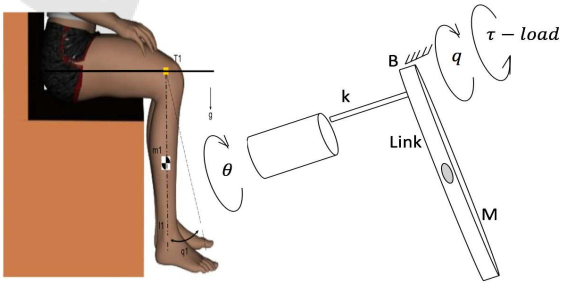

Figure 2: Model representation for knee rehabilitation.

To gain an insight of the control system behavior, and taking into account that our scope is to control the knee joint of the proposed assistive rehabilitation device, we will consider a one-DoF soft actuated model, which represents the knee joint, as shown in Fig.2, defined by

$$\begin{array}{rcl} \dot{q} & = & \omega_q, \\ \dot{\omega}_q & = & \frac{1}{M}(-kq - B\omega_q + k\theta + \tau_{load}) \end{array} \qquad (1)$$

where q and ω_q are the link (calf) angular position and angular velocity respectively; θ is the rotor (knee join) angular position, which is considered as an input to our system; τ_{load} is the load torque, and M, k, B are the mass, the stiffness and damping of the system, respectively. Consider that the vector state is defined as $X = [q,\ \omega_q]^T$.

In this paper we aim to control the link angular position of the knee rehabilitation device, to comply with defined repetitive motions. It is worth to mention that the soft actuators considered for the design have a low level PD control that assures that the desired rotor's angular position is indeed the input angular position[2] θ.

3 COMBINED FEEDBACK AND FEEDFORWARD CONTROL STRATEGY

In this section we present the design of the combined feedback and feedforward strategy, as shown in Fig. 3. We first describe the control strategy requirements based on the desired behavior of the patient's knee motion; then, we present the control law proposed.

3.1 Control Requirements

Let us describe Fig. 3. According to physical therapy indications (Umivale, 2011), the control law must keep the output position close to the desired reference with a smooth approach, so the Reference Block provides a saturated reference. In this case, the reference is the motor's angular position θ. Then, the saturated reference must be smooth in order to reach it with a soft response, i.e. similar to an overdamped system. Furthermore, the Feedback Block has an integral action that ensures that the system follows the desired reference and that disturbances are rejected.

The control strategy includes a feedforward action such that loading disturbances are compensated. Then, the Decision System Block acts as follows. When the system, i.e. the knee approaches to the final value, over a threshold of 20%, the speed with which it approaches to the reference is lower. This is done because when performing rehabilitation training, the patient slowers in the critical angular positions, according to physiotherapists criterion. If the force exerted by the patient is over the threshold, (e.g. because the patient is in pain), the system will send a zero reference to relax the patient's leg.

3.2 Control Design

Now, let us focus on the control design for the knee rehabilitation assistive device. Based on pole placement, we use low gains to approach the natural behavior of the human motion, when performing exercises to stretch and strengthen the knee muscles, guided by a physiotherapist.

Consider the linear model of the system in (1). Defining k_1, k_2 which are respectively the gain of the angular position q; the gain of the angular velocity w_q. Furthermore, defining k_i as the gain of ξ, where $\dot{\xi} = R - q$; R is the desired knee angular position of the rehabilitation system. Then, the feedback control law is defined by

$$\theta = k[k_2\omega_q + k_1 q + k_i\xi]. \tag{2}$$

Let us assume that the system is in equilibrium, this is $\tau_{load} = 0$. Then, the closed-loop dynamics are

$$\frac{q(s)}{R(s)} = \frac{k_i k}{Ms^3 + s^2(B - kk_2) + s(k - kk_1) + k_i k}. \tag{3}$$

Here we assure that the feedback design, i.e. $det(SI - A^*)$=0, is Hurwitz to tune the control coefficients, so the system is stable (pole placement). In a practical way, these coefficients modify the system dynamics. So to maintain the intrinsic dynamics of the system, i.e. the stiffness, the changes have to be such that the system response is close to the natural response. According to (Della-Santina et al., 2017), a low-gain of the feedback controller is required in order to have little stiffness alteration in the model. The main difference, and the contribution of this proposal is that we focus on the control design specifications for a soft actuated knee rehabilitation device (i.e. actuated by SEA or VSA), applying the sufficient condition derived in the previously mentioned work. The aim here is to maintain the intrinsic characteristics of the actuation system, this is to keep σ proportional to $q - \theta$.

Regarding stiffness, it is defined as $\frac{\partial T(q-\theta,\sigma)}{\partial q}$, where $T(q - \theta, \sigma)$ is the torque due to the compliant element at the joint, and σ is a parameter used to set joint stiffness in variable stiffness actuators. For the design of the position controller presented in this paper, we consider a constant stiffness.

In order to minimize the changes in the physical compliance, the stiffness value in closed loop has to remain in a δ-neighborhood of the value in the open loop, along the system reference signal. Then, let us consider that our controller is $\theta(q, \dot{q}, t, \sigma, r, \xi)$ as in (2). Then, the partial derivative $\frac{\partial\theta(\cdot)}{\partial q}$ results in the controller coefficients. Consider also that the natural stiffness along the system reference is defined as

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[2] http://www.qbrobotics.com/

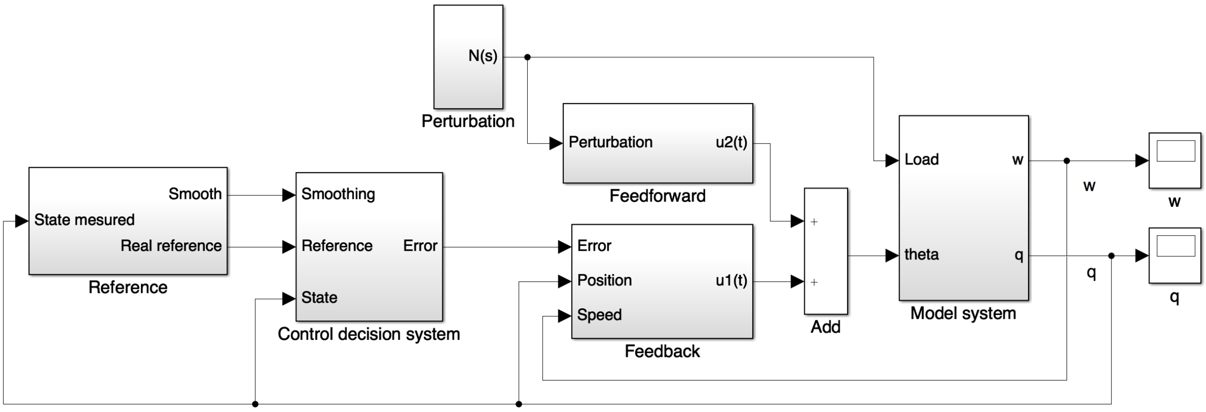

Figure 3: Control structure used in the rehabilitation system.

$\frac{\partial T(0,\sigma)}{\partial q}$, then, the sufficient condition to maintain the system stiffness is verified. In this case it is

$$\| \frac{\partial\theta(q,\dot{q},t,\sigma,r,\xi)}{\partial q} \| \leq \delta \| \frac{\partial T(0,\sigma)}{\partial q} \|^{-1}, \quad (4)$$

where r is the reference trajectory, R is the desired knee angular position, and ξ is the integral action on the error. When $\dot{\xi} = \Pi(q,\dot{q},t,\sigma,r,\xi)$ exists (4) becomes

$$\| \frac{\partial\theta}{\partial q} + \frac{\partial\theta}{\partial\xi}\frac{\partial\xi}{\partial q} \| \leq \delta \| \frac{\partial T(0,\sigma)}{\partial q} \|^{-1} \quad (5)$$

The main idea of (5) is that the coefficients of feedback part of the controller have to be sufficiently small, so we need to evaluate these coefficients in the case of the controller proposed here. If the right term in (5) is zero, there will be no stiffness variation due to the control action. This is $\| \frac{\partial\theta}{\partial q} + \frac{\partial\theta}{\partial\xi}\frac{\partial\xi}{\partial q} \| \leq 0$. Regarding the controller designed in this case, it is true that $\| \frac{\partial T(0,\sigma)}{\partial q} \|^{-1} = 0$, which meets the sufficient condition.

3.3 Controller Implementation

We choose k_1, k_2 y k_i sufficiently small, applying the poles placement method, according to the following criteria. Using a Robust Control Toolbox, we test the system to tune these values, such that with a variation up to 20% of k_1, and k_2, and up to 30% of k_i, the system is stable and the design specifications are met, i.e. low speed when approaching to the desired angular position, keeping the intrinsic stiffness of the system. Observe Figs. 4 and 5, which show respectively in time and frequency domain that the system is stable when there is a change of the control parameters.

In this way, the condition (4) is accomplished, as well as the control objective. Therefore, the natural motion achieved using soft actuation allows to perform assisted knee rehabilitation exercises. For the design and validation of the derived control law, we use a stiffness preset constant value of $\sigma = 6\,Nm/rad$.

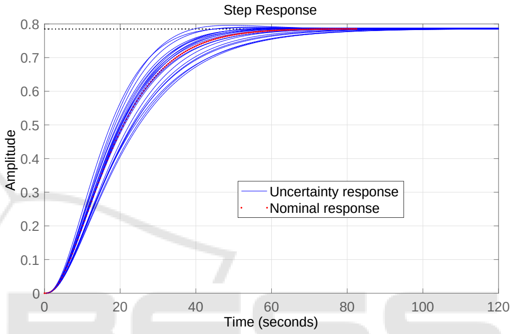

Figure 4: Variation of control parameters - Step response.

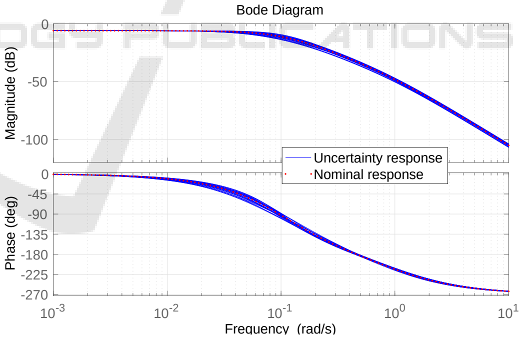

Figure 5: Variation of control parameters - Bode of the system.

4 RESULTS AND DISCUSSION

To analyze the results of the control strategy for the rehabilitation device, we design a test in simulation. We consider that the rehabilitation system can be con-

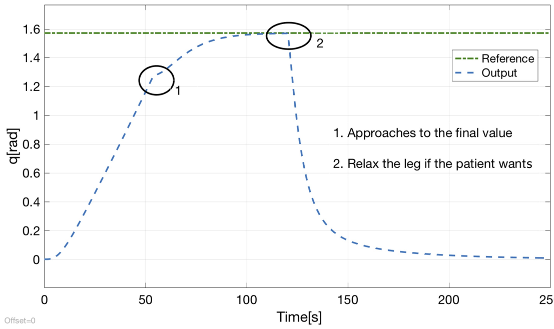

Figure 6: Tracking system.

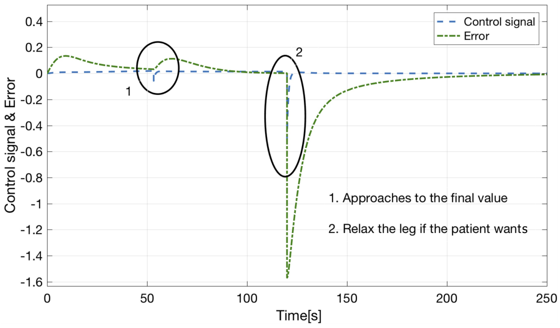

Figure 7: Input to the system and Error.

figured for patients heights h between 1.40 m and 1.90 m, and weight W between 40 kg and 90 kg according to mean normal adult population. According to anthropomorphic proportions we can establish mean length and weight of the leg according to h and W. For the simulations, the parameters correspond to a subject of $h = 1.60\ m$ and $W = 60\ kg$. Besides, damping and stiffness are obtained experimentally as $B = 1$ First, let us consider the feedback action. According to the proposed strategy, we define the reference for the angular position that the knee has to reach. When the angular position has achieved 80% of the desired value, the structure of the regulator changes by means of the integral action, making the response slower, compared to the system dynamics. It is worth to mention that the controller was designed such that the stiffness is not affected, so a change in the parameters will maintain this condition. Fig. 6 shows the system response to a reference $q_{ref} = \frac{\pi}{2}\ rad$. Notice that the output q follows the reference with zero tracking error. It is worth to mention that the input to the control system is a saturated reference thus it is close to the real state of the system. We observe that at time $t = 190\ s$, when the output reaches 80% of the final value, indeed the dynamic changes and the motion becomes slower, as desired (see point labeled as 1 in Fig. 6). Let us define that after $t = 300\ s$, the patient needs to stop the system (e.g. because of pain), then we simulate this requirement as an stop. In this case, the system has to go back to an initial configuration in order to relieve pain (see point labeled as 2 in Fig. 6).

In fig. 7 we show the control and error signals. Observe that there are no overshoots nor strong changes, keeping the system stable, guaranteeing a smooth motion for the knee joint.

Now, let us consider the feedforward action. The idea of this action is to reject disturbances. Then, we test the system with a step signal perturbation $\mu(t)$ which may represent for instance the corresponding component of the leg's weight, that is an available measurement of the system. The signal $\mu(t)$ acts from $t = 0\ s$ to $t = 100\ s$. In fig.8, the results of the control action are presented. Observe that the system performance with the disturbance is close to that when there is no disturbance, and that the response recovery starts at $t = 0\ s$ (see point labeled as 1 in fig.8). At the end of the disturbance, at $t = 100\ s$ the system recovers and continues to operate normally, as desired (see point labeled as 2 in fig.8).

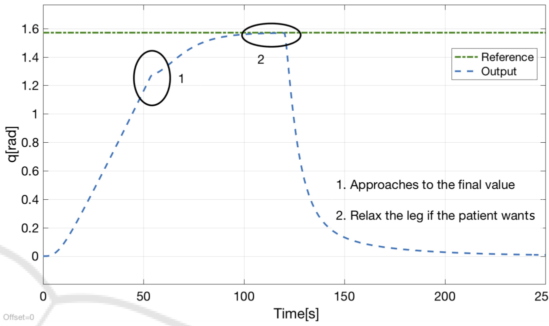

Figure 8: Tracking system with perturbation.

Referring to the control signals, due to the compliant behavior of the system it presents oscillations, which are properly compensated. These oscillations are due to the natural behavior of the system using soft actuation.

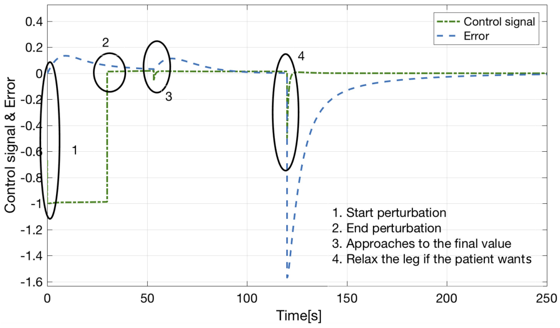

Figure 9: Input to the system and Error with perturbation.

5 CONCLUSION

In this paper, we have presented a global control strategy that combines feedforward and feedback actions for a soft actuated knee rehabilitation device. The designed device is a 5-bars-linkage underactuated system. However, to gain an insight of the control strategy and the requirements, we have presented an approach to control a soft-actuated-one DoF system, when performing the desired motion during physical knee rehabilitation. The specific requirements of the system, that we have proved to achieve with the proposed combined control strategy are to keep intrinsic stiffness of the system, stability, low velocity when approaching to the reference, and disturbance rejection. The feedforward strategy compensates loading disturbances while the feedback strategy acts in a defined threshold to maintain the stiffness of the system. When approaching the 80% of the reference, we switch the control parameters in order to have a lower velocity near to the reference, meeting the desired specifications. In future works, we will study the validity of the control strategy in the 5-bars-linkage-rehabilitation device.

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