Powered Knee Orthosis for Human Gait Rehabilitation: First Advances

Paulo Félix[1], Joana Figueiredo[1], Cristina P. Santos[1], and Juan C. Moreno[2]

Abstract— **This paper presents a new system for a powered knee orthosis, that was designed to assist and improve the gait function of patients with gait pathologies. The system contains the orthotic device (embedded with sensors for angle and user-orthosis interaction torque measurements, and an electric actuator) and wearable sensors (inertial measurement unit, force sensitive resistors, and electromyography sensors), which allows the generation of smart rehabilitation tools and several motion assistive techniques. The main goal is to present a conceptual overview and functional description of the system and use scenarios of each component. The attachment mechanism of the orthosis to the limb is also highlighted, being composed of a straps system fixed in the mechanical links of the joint. It was noticed that users with distinct lower-limb morphologies can presents difficulties wearing the orthosis, since the device needs constant adjust to align the mechanical and human joints. The system was validated in ground-level walking on healthy subjects, with emphasis on the impact of the device in the user. The subjects reported that the orthosis is comfortable to use, easy to wear, and no issues were raised regarding the aesthetics of the device. Only the weight was assimilated as a possible hindrance (compensated in the future). Future challenges involve the inclusion of an ankle joint in the system and the use of the proposed tool in rehabilitation.**

I. INTRODUCTION

In gait rehabilitation, therapies assisted by powered robotic devices for treating limb impairments are increasingly being used in addition to conventional therapeutic approaches. These devices are addressed as tools to relive the repetitive and heavy work of physical therapists while improving (neurologic or orthopedic) patient's recovery effectiveness [1]. They provide a high degree of training with specific and repetitive tasks, and objective measurements of the patient's outputs in terms of joint kinematics and kinetics [2].

Lower-limb orthoses and exoskeletons have been widely considering. They consist in wearable active mechanical devices, anthropomorphic in nature and fit close to the body, that are capable of acting in parallel with the human limb to increase the human locomotion economy, augment joint strength, and increase endurance [3]. While exoskeletons are often described as devices capable of augmenting the performance of an able-bodied wearer, active orthoses increase the ambulatory ability of a person suffering from a specific leg pathology [4]. These systems are equipped with wearable and/or embedded sensors (e.g., gait kinematics, gait kinetics, and electromyography fields) [1], [4], which provide information very correlated with the user's locomotion [5], and an actuation system (e.g., electric, pneumatic, hydraulic, and SEA - series elastic actuators) [4], capable of providing the required torques and speeds in specific application. Together, these components are used by advanced controllers, to assist the patients through several strategies (e.g., sensitivity amplification, pre-defined gait trajectory control, model-based control, adaptive oscillators-based control, fuzzy control, predefined action based on gait pattern, hybrid assistive strategy, muscle stiffness control, and proportional myoelectrical control) [1]. Additional, these devices must also be mechanically compatible with the human anatomy, able to safely move in concert with the user without obstructing or resisting movement [6].

The main goal of our proposal is to present a Powered Knee Orthosis (PKO) system, embedded with wearable sensors suitable for gait analysis and control. The proposed system was designed as a setup that can potentially be used with data processing approaches to generate smart rehabilitation tools or adaptive joint motion assistances. The selected wearable sensors (i.e., Inertial Measurement Units (IMUs), Force Sensitive Resistors (FSRs), and Electromyography (EMG) sensors) are very popular in the literature, given their effectiveness, reliability and accuracy. Their combination gives way for a more complex setup, to a point that goes behind the KO domain, and extends to feet plantar pressure analysis, gait pattern analysis and segmentation, intention recognition and disability level evaluation. Additionally, the active orthosis has embedded sensors for angle and torque measurements, and an electronic actuator, which are combined with the wearable sensors for the motion assistive strategies.

In general, active orthoses are designed to assist in distinct limb's pathologies. Particularly, the presented KO was designed to improve the gait function of neurological patients, showing high potential for numerous application on gait rehabilitation field. For that matter, studies have also been focused on using the least number of sensors for gait analysis and assistance. Overall, this paper presents a conceptual overview and functional description of the system, and use scenarios for each component, highlighting their role in the system and future use.

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[1] Paulo Félix, Joana Figueiredo, and Cristina P. Santos are with Center for MicroElectroMechanical Systems (CMEMS), University of Minho, Guimarães, Portugal (e-mail: {a61767,id6003}@alunos.uminho.pt, cristina@dei.uminho.pt).

[2] Juan C. Moreno is with Neural Rehabilitation Group, Cajal Institute, Spanish National Research Council, Madrid, Spain (e-mail: jc.moreno@csic.es).

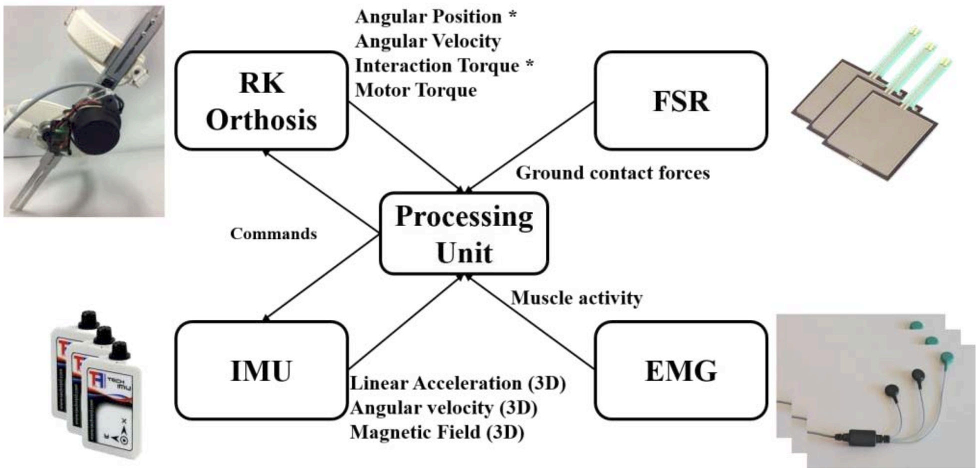

Figure 1 – System's overview. The system is composed by the Right Knee (RK) orthosis, IMUs, FSRs, and EMGs, centralized in a processing unit. The sensors used in motion assistive techniques already implemented are highlighted in (*).

II. PROPOSED SYSTEM

The system proposed in this paper is intended for gait rehabilitation of the lower limbs, particularly, to control position and motion of the knee joint while compensating weakness or correcting deformities. Thus, the system is equipped with a PKO and sensors for monitoring and control the user's movement, and a central processing unit capable of running control strategies, as illustrated in Fig. 1.

A. Powered Knee Orthosis

The PKO presented is based on technology developed for the lower limb robotic H2-exoskeleton (Technaid S.L., Spain), a full-body system designed to assist stroke survivors [7]. A conceptual overview of the system is presented in Fig. 1. A detailed technical description can be found in Félix *et. al* [8]. Regarding the information collected from the orthotic device, instead of being attached to the human joint, these sensors are embedded in the device, along with an electric actuator, not raising issues related to safety, comfort, reliability, and donning process. From the device, distinct information can be collected, as follows.

1) Angular Position, Angular Speed, and Motor torque

These physical quantities are measured indirectly by a precision potentiometer (Vishay) and Hall effect sensors, respectively. The angular position can be used to control the trajectory of the knee joint and to estimate gait phases or events. Imposed trajectories to the joint are suitable for therapies with repetitive movements, which can improve muscular strength and movement coordination. Additionally, monitoring the joint's angle and velocity in long-term periods can allow the detection of pathologies. Moreover, the motor torque can be used to determine the actuator torque, allowing the design of strategies that control the joint torque.

2) User-Orthosis Interaction Torque

The interaction torque is measured by strain gauges. The kinetic data can be used in learning strategies that minimize the mechanical impedance of the joint to act like a passive actuator. Also, therapies with the impedance of the joint variable over the gait pattern (impedance control with stiffness, damping and/or inertia variable) have also been considered [9]. Moreover, the interaction can be used to indirectly estimate the user's intentions and evaluate the user's effort in specific tasks.

3) Electric Actuator

Literature suggests that electric actuators provide a reduction in power consumption during gait [10], being widely used in most ambulatory knee orthosis systems [11]–[15]. Thus, the actuation mechanism is based on a DC motor coupled to a gearbox (strain wave gears), able to provide higher torque at lower speed. The DC motor selected (brushless DC motor EC60-100W; Maxon) constitute an efficient, portable, and reliable solution, having reduced noise, longer lifetime, and reduced electromagnetic interference. Regarding the use of a coupled gearbox (Harmonic Drive), this solution stands for having no backlash, compactness, high gear ration, high torque capability, and good resolution.

B. Wearable Sensors

For gait analysis and control proposes, the system is incorporated with external wearable sensors. Through gait analysis, gait phases and events can be identified, kinematic and kinetic parameters can be determined, and musculoskeletal functions can be quantitatively evaluated [5]. In general, an accurate and reliable knowledge of human characteristics at a given time or monitoring over time can also provide early diagnosis [16]. Thus, the selected external sensors (i.e., IMUs, FSRs, and EMGs) were chosen to cover the three main areas of gait analysis methods, in particular, kinematics, kinetics, and EMG, being suitable for innumerous applications in orthopedics and gait rehabilitation [5]. Particularly, these sensors were chosen as optimal solutions, being compact, small, light, low-cost and low-power.

1) Inertial Measurement Unit

An IMU is an electronic device often used to measure and report the object's velocity, acceleration, orientation, and gravitational forces. The selected IMU (Tech IMU v4, Technaid S.L., Spain) is an optimal solution for the system, since it incorporates tri-dimensional (3D) inertial sensors (i.e., accelerometers, gyroscopes, and magnetometers), providing information in 4 distinct forms (digital, physical, DCM orientation, and quaternions), and finally, it only allows the communication through a physical network (control area network) that can be easily expanded to connect other similar IMUs. When placed on the limbs (e.g., foot, shank, tight, and joint), kinematic analysis using the information collected can be performed to recognize gait phases and events, as well as to obtain general gait parameters (e.g., position, step detection, and stride length) and movement information of the user segment (e.g., type of movement, physical activity level, and fall detection) [5], [16]. Furthermore, inertial measurements can be used in advanced control algorithms to assist the knee joint, specially the angular position [9], [12], [13], [15], [17].

For this application, the IMU is mounted on the instep of the foot to detect the gait events during walking, using the data recorded by the gyroscope. Later, it is expected to use the segmentation of the gait pattern in high-level assistive techniques to provide a more custom assistance in some moments of the gait. Also, the output of these inertial sensors will be used in machine learning based techniques for recognition of user's motion intentions.

2) *Force Sensitive Sensors*

A gold standard widely used in kinetics and spatiotemporal gait analysis is the FSR sensor. FSRs measure the ground reaction forces under the foot, returning a voltage proportional to the pressure measured. Feet plantar pressure data can be used in gait pattern segmentation and in the determination gait parameters (e.g., step detection and length) [5], [16].

In the presented system, the chosen sensors (406 FSR, Interlink Electronics) were mounted in the heel and foot of the user, allowing to detect the gait phases and events.

3) *Electromyography*

The measurement of EMG is an important method for clinical gait analysis. EMGs detect and measure the small electric current produced by muscles during contractions (voluntary and involuntary). On an active muscle, EMGs can yield information about the muscle physiology and motor control during walking. Furthermore, EMG monitoring can identify neural injury or compression, or primary pathological processes [5]. For gait specific applications, EMGs can be used to measure gait characteristics, such as, gait phases (by analyzing kinematics plots of joint motion compared with EMG plots) and muscle effort during walking [16]. Moreover, some knee orthosis systems use the relative muscle tension recorded by these sensors to control the movement of a joint [11].

In the proposed system, EMGs were integrated to measure the muscle activity of the main muscles that contribute to the movement during walking (e.g., *tibialis anterior* and *gastrocnemius* muscles, and *hamstrings* and *quadriceps femoris* muscles). We selected an EMG preamplifier (MA-420, Motion Lab Systems) and developed additional electronic for the proper amplification, conditioning, and acquisition of the signal by the processing unit. It is intended to use the data collected to monitor and evaluate the user's effort and disability level during walking, wearing the orthosis. Moreover, a EMG-based control strategy is being designed as an additional assistive strategy.

C. *Strap System*

To achieve a proper attachment of the orthosis to the limb, we incorporated 4 straps in the system (shown in Fig. 2), in the extremity of lower and upper link (both connected to the joint). The goal is to align the mechanical joint with the human joint, minimizing loss of mechanical power without obstruction or resistance to the movement. Also, the links are also adjustable in order to fit users with different height and leg's length.

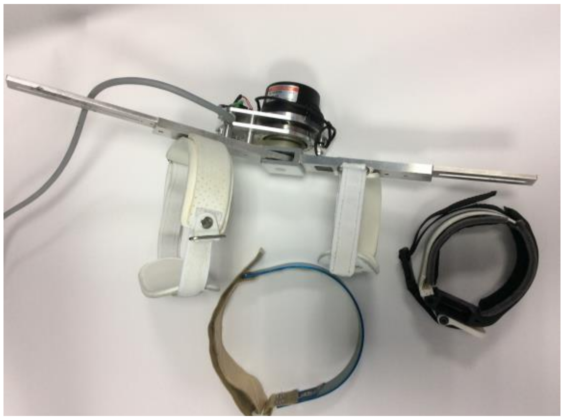

Figure 2 – Orthosis with straps used to fix the device to human's limb.

D. *Applications*

Powered knee orthoses are designed to assist the users in a set of activities and applications. Patients with neurological disorders (e.g., stoke survivors, patients with multiple sclerosis and affected by the poliomyelitis virus) and/or with deficits at the knee joint (e.g., *genu recurvatum*) [18] [14] are good candidates for robotic therapies, since they present gait impairments during walking. Furthermore, knee orthoses can be used in daily life activities, including climbing stairs [17], squatting with or without heavy loads [17], [12], [19], stand-to-sit and sit-to-stand tasks [19]–[21], and running [15].

III. VALIDATION

To validate the whole system, we conducted experiments with healthy volunteers walking in level-ground on a treadmill for different speeds (up to 2 km/h). The participants were asked to wear the orthosis and walk in well-defined trajectories. To evaluate the effects of wearing the orthosis, i.e., its impact on the users, each subject was questioned regarding the performance of the knee joint in terms of comfort level, weight, aesthetic and easy of wearing. Additional, the strap system was also validated with the experiments. For each subject, the orthosis straps were adjusted to ensure a correct alignment of both joints. Fig. 3 shows the whole system fixed in two subjects during the experiments.

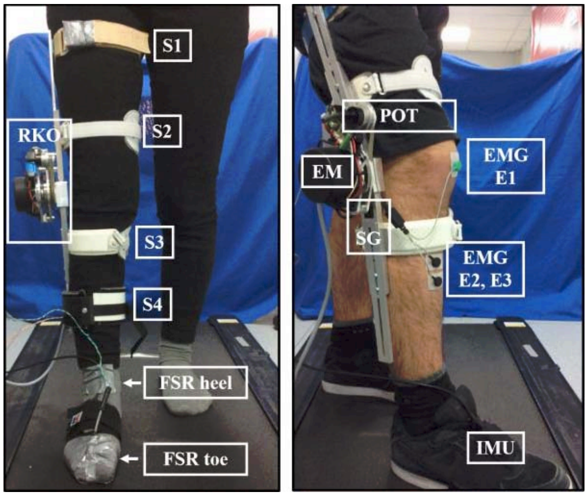

Figure 3 – Knee orthosis system and wearable sensors mounted in two subjects, composed by RKO (right knee orthosis), 4 straps (S1-S4), FSRs (FSR toe and heel), electric motor (EM), potentiometer (POT), strain gauges (SG), EMG electrodes (EMG E1-E3), and IMU.

IV. RESULTS AND DISCUSSION

The results obtained show positive contributions. The system conveniently allowed all subjects to achieve walking under pre-defined joint trajectories and the assistance of the orthosis.

Regarding the way that it was fixed to the limb, a strap system was used and attached to the mechanical parts. Fig. 3 shows the whole system fixed on two subjects during the experiments. In some cases, the device was not completely attached and aligned with the human joint, because of the distinct morphology of the lower limb that some subjects present. These users were able to perform the trials, although it was necessary to constantly readjustment of the orthosis' position. Regarding the PKO's impact on the user during the experiments, the subjects reported that the orthosis is comfortable to use (they did not feel pain), easy to wear, and no negative aspects were raised about the aesthetics of the device. Only the weight of the orthosis was assimilated as a potential hindrance, however, it will be compensated in the future.

V. CONCLUSIONS AND FUTURE PERSPECTIVES

In this paper, first advances of a PKO system are presented, as a setup that can potentially be used to generate smart rehabilitation and adaptive joint motion assistances. The system was validated regarding its well-positioning and effect in the users. An overview of possible applications of the orthosis and sensors was also carried out. The results are promising considering that the group of users was able to wear the orthosis and perform pre-defined trajectories during level-ground walking at different speeds.

Futures challenges involves the use of the propose assistive device in diverse applications of neurorehabilitation. An ankle orthosis (same sensors and actuator) will be incorporated in the system, to provide assistance in other pathologies presented in neurological patients (such as drop foot). Moreover, an assisted-as-needed strategy is being developed to control the human-orthosis interaction and encourage the user's participation in the treatment.

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