Instrumentation and validation of polymer optical fiber sensor technology on a knee exoskeleton

Jonathan Campo Jaimes
Mechanical Engineering Department
University of São Paulo
São Carlos, Brazil
jonathancj@usp.br

Arnaldo G. Leal-Junior
Mechanical Engineering Department
Federal University of Espírito Santo
Vitoria, Brazil
leal-junior.arnaldo@ieee.org

Adriano A. G. Siqueira
Mechanical Engineering Department
University of São Paulo
São Carlos, Brazil
siqueira@sc.usp.br

Anselmo Frizera
Electrical Engineering Department
Federal University of Espírito Santo
Vitoria, Brazil
frizera@ieee.org

***Abstract*—In this paper is presented the construction, characterization, and evaluation of POF sensors for joint angle measurement and human-robot interaction torque assessment on a knee exoskeleton. Experimental tests with a voluntary user demonstrated the feasibility of these sensors on sitting position exercises. The results encourage us to work toward the implementation of this assembly in a six joint lower limb exoskeleton and to study robot control strategies based on POF sensor information.**

***Index Terms*—POF curvature sensors, robotic rehabilitation, joint angle, human-robot interaction forces**

I. Introduction

Recent trends in robotic rehabilitation strategies use every time more information about biosignals to develop tailored procedures for patients recovery [1], [2]. However, providing biosignal data about the patient in robotic rehabilitation scenarios involves sensor system challenges like electromagnetic field immunity, the complexity of signal processing, and short time fixation. One of the emerging sensor technology solutions to deal with these issues are Polymer Optical Fiber (POF) sensors. They have been used for monitoring of physiological parameters for human health assessment [5] such as angle joints [4] or torque [8] and human-robot interaction force [6]. The POF-based sensors measure the intensity power variation of the optical element that is proportional to a curvature angle generated when the fiber is under bending effects. As a part of the continuous effort to design high-performance control strategies of our EXO-TAO exoskeleton [9], this paper presents the application of the above POF application studies on the EXO-TAO for joint angle measurement and interaction torque assessment. The rest of this paper contains the experimental setup, the characterization of the developed POF sensors, and the evaluation with a voluntary user.

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II. Methods

A. Experimental setup

In this work, it is proposed to use a modular configuration of the EXO-TAO as a knee exoskeleton. Figure 1 shows the instrumentation of the EXO-TAO with POF sensors for the joint angle measurement and human-robot interaction assessment. The POF sensor one measures the knee passive joint; it was positioned in the knee exoskeleton in such a way the sensitive zone is located at the geometric center of the rotary joint, and the whole fiber is aligned with the tubular axes. The function of POF sensors 2 and 3 is to assess the interaction torques produced by the contact between the robot joint and the human leg. The POF based torque sensors were positioned inside the lateral sections of a shank support of the exoskeleton. Since the device is delimited for knee joint movements in the sagittal plane, the contact between human and robot can be converted to torque. The assembly of the POF torque sensors consisted in encapsulating the optical fiber between two different 3D-printed materials: a rigid one (Polylactic Acid (PLA)) for fixation to the lateral section of the shank support and a flexible (Thermoplastic Polyurethane (TPU)) that transmits the human-robot contact force to the fiber without being in direct contact.

For each of the three POF sensors, the light source is provided by a Light emitting diode IF-E97 (Industrial Fiber Optics, USA) at one end of the fiber and detected at the other end by a phototransistor IF-D92 (Industrial Fiber Optics, USA). Regarding the POF angle sensor, the LED was fixed on a 3D-printed support coupled to the tubular structure, and the phototransistor was on a 3D-printed slide base to avoid undesired displacement when bending the fiber. Since the curvature angle of the POF force sensors do not require linear displacement of the fiber, their LEDs and phototransistors were fixed on 3D-printed supports also coupled on the tubular structure but beside the shank support. A microcontroller FRDM-KL25Z board (Freescale, Austin, TX, USA) was used

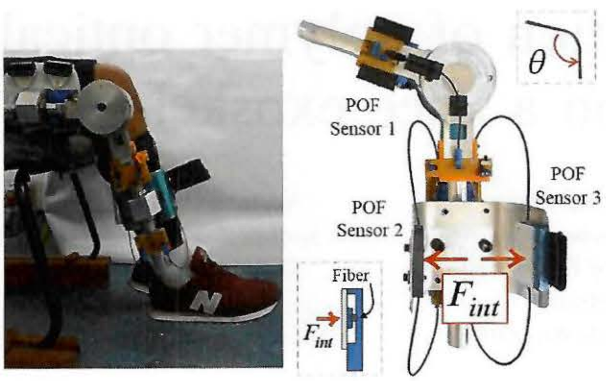

Fig. 1: Experimental setup. θ is the knee angle.

for the raw data acquisition and the light power supply for all the three POF sensors.

B. Characterization

Concerning the angle POF sensor, a test consisting in increasing the angle passive joint from 0 ° to 70 ° with steps of 5 ° at each 20 second was made. In order to provide a reference signal of the angle joint, the knee joint device was equipped by a rotary absolute encoder (AksIM by RLS Enterprise) with 16 bits of output resolution.

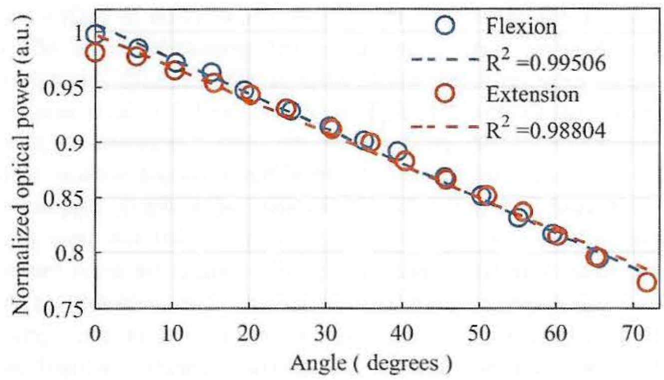

Fig. 2: Linear regression for angle characterization.

Figure 2 shows the POF sensor output concerning the joint angle for flexion and extension movements (blue and red circle markers, respectively). A linear regression shows the relation between the angle joint and the POF power output for flexion (blue dashed line) and extension (red dashed line) showing sensitivity close to 8.2 mV/° and 7.8 mV/°, respectively. In order to characterize the POF torque sensors with a known torque, the user was asked to stand up and to maintain his knee joint angle in a fixed position while the knee exoskeleton applied extension and flexion torques from 0 to ± 5 N-m. By doing this, the knee angle is maintained in the zero position, and the commanded actuator torques are completely transmitted to the POF torque sensors. Three tests were performed for each extension and flexion torques, Figures 3 and 4 shows the

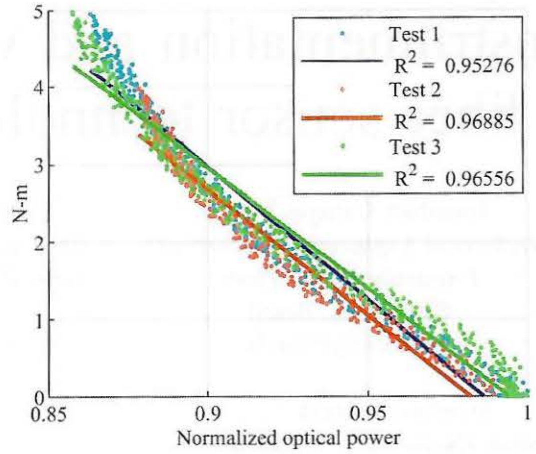

Fig. 3: Characterization for extension tests.

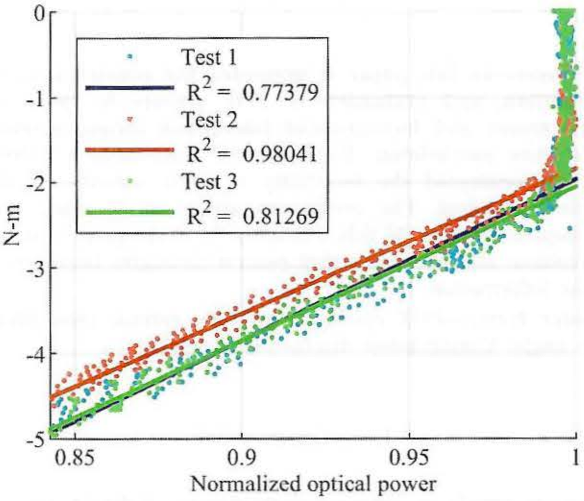

Fig. 4: Characterization for flexion tests.

POF output and torque correlations and linear regressions for the tests of extension and flexion respectively. The regressions yielded uniformity with sensitivities close to 32 mV/N-m for extension and 18 mV/N-m for flexion torques.

III. RESULTS

Two experiments were carried out with a voluntary user to evaluate the instrumented knee exoskeleton. The first experiment was intended to verify the POF angle sensor. To this, the user was asked to perform seated knee extension/flexion movements in a range of [0 - 70] ° and a period of 25 seconds while the POF angle sensor output and the encoder were collected. Figure shows the corresponding time responses for the POF angle sensor output and the angle given by the encoder (reference). The estimated angle using the regression corresponding for the POF sensor one is plotted together with the encoder data.

The second experiment was intended to evaluate the POF torque sensors. The user was asked to maintain his knee joint

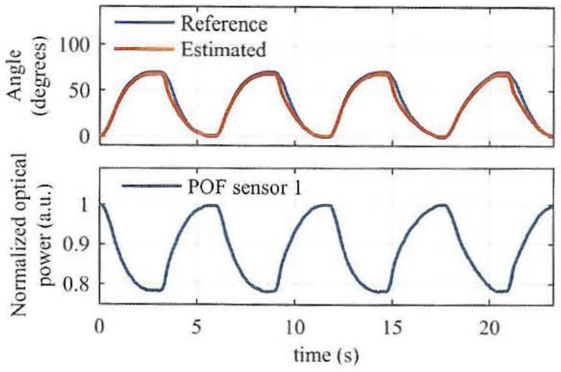

Fig. 5: validation of POF angle sensor.

while the exoskeleton provided a square wave torque signal, with amplitude ± 5 N-m. Figure 6 shows the time responses for the actuator (blue) and reference (dashed) torques, as well as the produced by the POF sensors 2 (red) and 3 (green). The gray boxes indicate the frames of the experiment when POF sensors 2 and 3 measure the extension and flexion torques, respectively. The POF sensors 2 yielded a peak extension torque of 4.18 N-m while POF sensor three a peak flexion torque of 4.23 N-m. Compared with the actuator torque, these values differ from 0.82 N-m and 0.77 N-m. One possible reason for the above said is that the contact forces are distributed around the surface of the shank support surrounding the leg, which may prompt losses in the measuring of the torque.

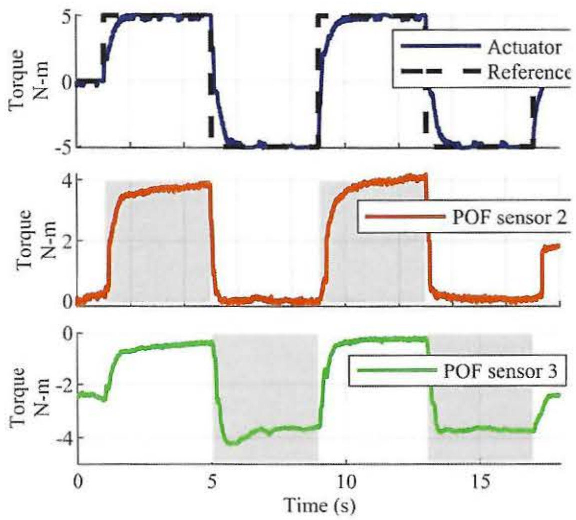

Fig. 6: Validation of POF torque sensors

IV. Conclusion

In this work was presented the instrumentation of a knee exoskeleton with POF technology for the joint angle measurement and for interaction torque assessment. The assembly was based on recent developments in the use of POF curvature sensors for healthcare devices. The POF sensor for angle measurement demonstrated high precision in the validation test. The POF torque sensors were able to give output responses close to the expected. Nevertheless, this finding suggests that the actuator force was no completely transmitted to the POF sensors. We are aware of improving the assembly of these torque sensors to get more precise sensitivities and to deal with the issue of the contact area between the leg and the shank support. This work represents an ongoing contribution of the presented in [10]. We intend to advance toward the development of control strategies for the EXO-TAO considering human joint angles and human-robot interaction forces given by POF curvature sensors.

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