Optical fiber force myography sensor for assessing lower limb movements

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ABSTRACT

Assessing lower limb motions is crucial for several applications in biomechanics and human-computer interaction. Nowadays, the displacement of lower limb joints is retrievable through piezoresistive strain gauges, magnetic sensors, and inertial measurement units, whereas non-invasive alternatives comprise surface electromyography (sEMG), brain-computer interfaces, and optical tracking. However, most prevailing technologies demand expensive, intricate hardware with multiple channels and rely on burdensome signal/video processing. Therefore, this paper presents an optical fiber sensor for assessing lower limb motions employing the force myography (FMG) technique. FMG predicts user movements and intentions from the radial pressures exerted by leg muscles, providing an intuitive force-level response and demanding fewer channels than the sEMG. Besides, fiber sensors are immune to variations of skin impedance and electromagnetic noise, circumventing the drawbacks of widespread force-sensing resistors and capacitive devices. In this work, a microbending optomechanical transducer converts muscle stimuli into light-intensity modulation, generating FMG waveforms that carry information about performed postures or movements. Firstly, experiments evaluated the average intensity versus knee joint displacements (0 to 120°) by attaching the optical transducers to the vastus intermedius and gastrocnemius/soleus muscles, achieving an average resolution of 5.4°. Subsequently, we measured the sensor response to different movements to characterize and classify the performed actions according to their waveforms. The results demonstrate the sensor's feasibility for detecting lower limb motions based on a straightforward and non-invasive setup, motivating further applications in robotic exoskeletons for walking assistance and rehabilitation.

Keywords: Force myography, optical fiber sensors, assistive technologies

1. INTRODUCTION

Assessing lower limb movements is crucial for diverse applications comprising assistive robotics, rehabilitation devices, motion capture, virtual reality, and human-computer interfaces. Optical tracking systems based on traceable markers and image features are available for retrieving postures and motions.[1] However, this approach presents limitations regarding intensive processing and occlusion. Alternatives include inertial measurement units and strain gauges attached to the lower limb's joints and links.[2] Despite their precise response enhanced by data fusion algorithms, such wearable devices impose additional load and may impair natural movements. Ultimately, surface electromyography (sEMG) and brain-computer interfaces arise as non-invasive solutions for predicting users' motions and intentions, though still relying on noisy signals and expensive apparatuses.[3]

Force myography (FMG) emerges as a promising technology to circumvent these limitations. FMG systems detect radial muscular contractions to retrieve forces, movements, or intentions. Unlike sEMG, the mechanical signals represent intuitive pressure levels instead of intricate electric waveforms, leading to recent applications in upper and lower limb assistance.[4] Nevertheless, current approaches employing arrays of piezoresistive transducers are vulnerable to sweating and skin impedance changes besides demanding excessive measurement channels.

Therefore, this pilot study presents an FMG system based on optical fiber sensors for detecting lower limb movements. We previously created a robotic glove for hand rehabilitation with fiber transducers coupled to the forearm, combining FMG and functional electrical stimulation (FES).[5] Thus, we extend such developments to

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assess the knee joint angle and analyze the optical signals acquired for selected actions like walking and jumping, providing valuable insights toward assistive exoskeletons and rehabilitation systems.

2. MATERIALS AND METHODS

2.1 Optical fiber FMG sensor

Figure 1 depicts the sensor setup. The white LED source illuminates a silica multimode fiber (MMF, core/clad diameters of 62.5/125 µm) through a launching stage. A 60 mm×15 mm optomechanical transducer printed in acrylonitrile butadiene styrene (ABS) polymer contains a pair of periodic corrugated structures (0.5 mm spacing) that enclose the MMF and induce microbending losses. Subsequently, a CCD camera (15 fps) acquires the modulated optical signal for further processing by MATLAB (Mathworks) routines. The developed application acquires output beam images and computes the average intensity for square 100×100 pixels regions of interest. Lastly, it normalizes and rescales the intensity levels, assuming the initial posture as the reference.

Moving the lower limb joints contracts the associated muscles and changes their volume. Transducers attached to those muscles perceive the exerted forces, pressing the MMF. The repetitive curvatures couple the core modes to radiation modes, yielding optical loss.[6] Thus, one may evaluate the mechanical stimuli from the output light intensity deviations and correlate them to the performed motion.[7]

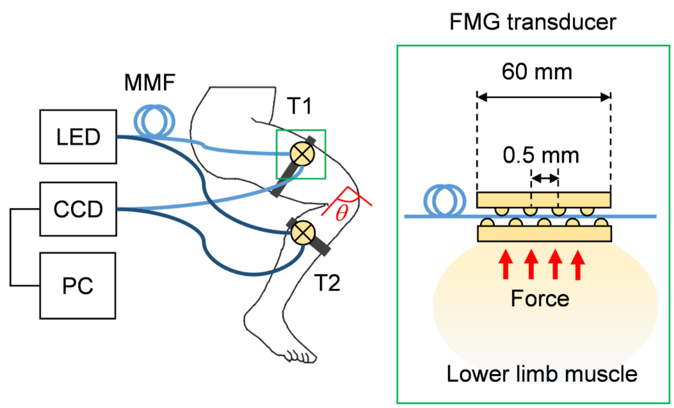

Figure 1. Experimental setup comprising an LED source, multimode fiber (MMF), CCD camera, computer, and transducers T1 and T2 attached to the thigh and calf muscles, respectively, by Velcro straps. θ indicates the knee joint angle. Inset: microbending transducer with a corrugate structure that modulates the fiber according to the input force.

2.2 Experimental procedure

We conducted this pilot study following the Ethics Committee recommendation, considering a single healthy volunteer with previous knowledge about the protocols. After deciding the transducers' placement by palpation, we firmly attached the microbending devices to the vastus intermedius (thigh) and gastrocnemius/soleus (calf) muscles of the right member using Velcro straps, as shown in Fig. 1, establishing a minimum preload yet ensuring comfort to the user.

Firstly, we evaluated the effect of knee joint angle θ in the FMG signal. The individual sat in an office chair with the knee extended at $\theta = 0°$ and the feet suspended to avoid contact with the floor. After receiving an auditory command, the individual flexes the knee by lowering the leg until it reaches the reference angle certified by a goniometer (2° resolution), keeping this position for 3.5 s before returning to the initial state. Experiments comprised angles $0 \leq \theta \leq 120°$, assuming five repetitions per θ.

Afterward, we investigated the FMG waveforms with the volunteer accomplishing different motion patterns in place: (i) walking normally, (ii) marching by lifting the knee, (iii) jumping, (iv) crouching, and (v) sitting/standing up from a chair. Each series comprised five repetitions.

3. RESULTS AND DISCUSSION

Figures 2(a) and (b) present the normalized intensity I as a function of the knee joint angle θ for the transducers placed in the thigh and calf, respectively. Each data point summarizes the average of five repetitions, and the error bars indicate the standard deviation of the mean with a probability level of 95%. I assumes a minimum value for $\theta = 0°$ because the muscles contract with the knee extension, establishing an initial pressure that excites the microbending device. Such mechanical load gradually drops as the volunteer flexes the joint, relaxing the muscles and reducing the optical loss, i.e., the average intensity increases. The sensitivities for the thigh and calf transducers are $\mathrm{d}I/\mathrm{d}\theta = 8.79 \times 10^{-3} (°)^{-1}$ (average resolution of $\Delta\theta = 5.4°$) and $\mathrm{d}I/\mathrm{d}\theta = 7.63 \times 10^{-3} (°)^{-1}$ ($\Delta\theta = 17.8°$), respectively. Albeit exhibiting a linear response, the calf sensor experienced wider deviations due to the influence of ankle and foot joints since the Velcro strap embraces an ensemble of overlaid muscles, modulating the transducer with the overall force.

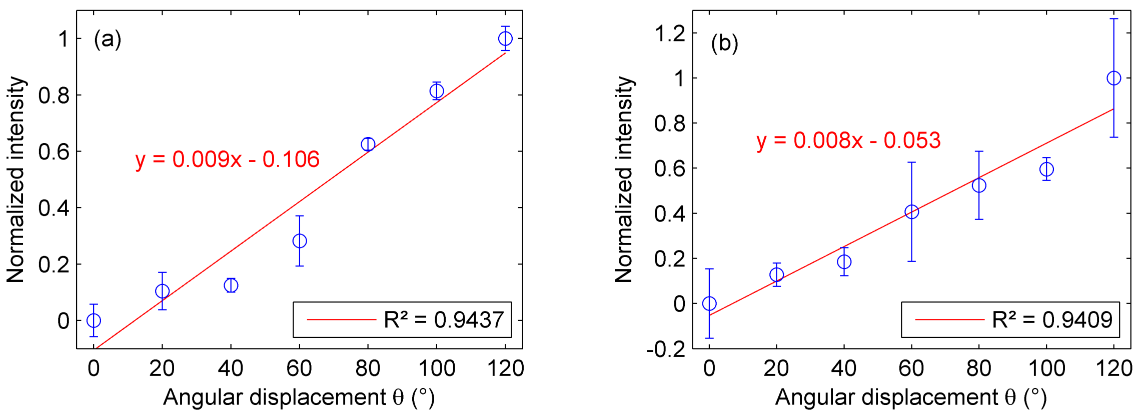

Figure 2. Normalized intensity as a function of the knee joint displacement for FMG transducers placed on (a) thigh and (b) calf. Solid lines are linear curve fittings.

Figure 3 illustrates the FMG signals acquired by the thigh transducer regarding selected actions. Walking in place requires lifting the leg with subtle knee joint flexion. The light attenuation in Fig. 3(a) indicates that the muscle hardens when the volunteer suspends the thigh, followed by intensity level recovery as the right leg touches the ground. Then, the knee extends to support the body while the left leg proceeds the gait. It is worth noticing that the vastus intermedius contraction differs for standing and sitting conditions, which explains the reduction in the I signal as θ increases. Conversely, the march pattern in Fig. 3(b) depicts a pair of dips with different amplitudes. The first (deepest) signalizes an acute knee flexion, whereas the latter is probably due to the impulse needed to raise the left limb. Jumping also produces a sharp dip, succeeded by contraction in the landing impact, then relaxation, as shown in Fig. 3(c). The crouching action in Fig. 3(d) also demands large angular displacements, though the intensity changes are less abrupt because the individual controls the movements' speed to avoid injury. Ultimately, Fig. 3(e) illustrates the intricate waveform obtained for the sit/stand-up procedure. Once sat in the chair, the volunteer stands up without hand assistance, which demands some effort of the lower limbs to raise the body. The FMG signal starts with a constant, attenuated level because the individual sits with the knee joints flexed. Attempting to stand-up causes a temporary relaxation of the thigh muscles, followed by an intense contraction when the feet touch the ground to suspend the hip. The average intensity restores to $I \approx 1$ after reaching the standing position, whereas sitting promotes a rapid knee flexion prior to the rest state.

The results endorse the sensor's feasibility in quantifying the angular displacement of single joints and recognizing assorted in-place movements. Mechanical signals provide a straightforward description of performed motions, avoiding cumbersome feature extraction and classification algorithms demanded by sEMG. Moreover, experiments proceeded with a single optical fiber transducer instead of multiple force-sensing resistors, suggesting a reliable operation with minimum measurement channels. One anticipates integration with an FES module for rehabilitation purposes,[5] recalling that optical fibers are immune to electromagnetic interference.

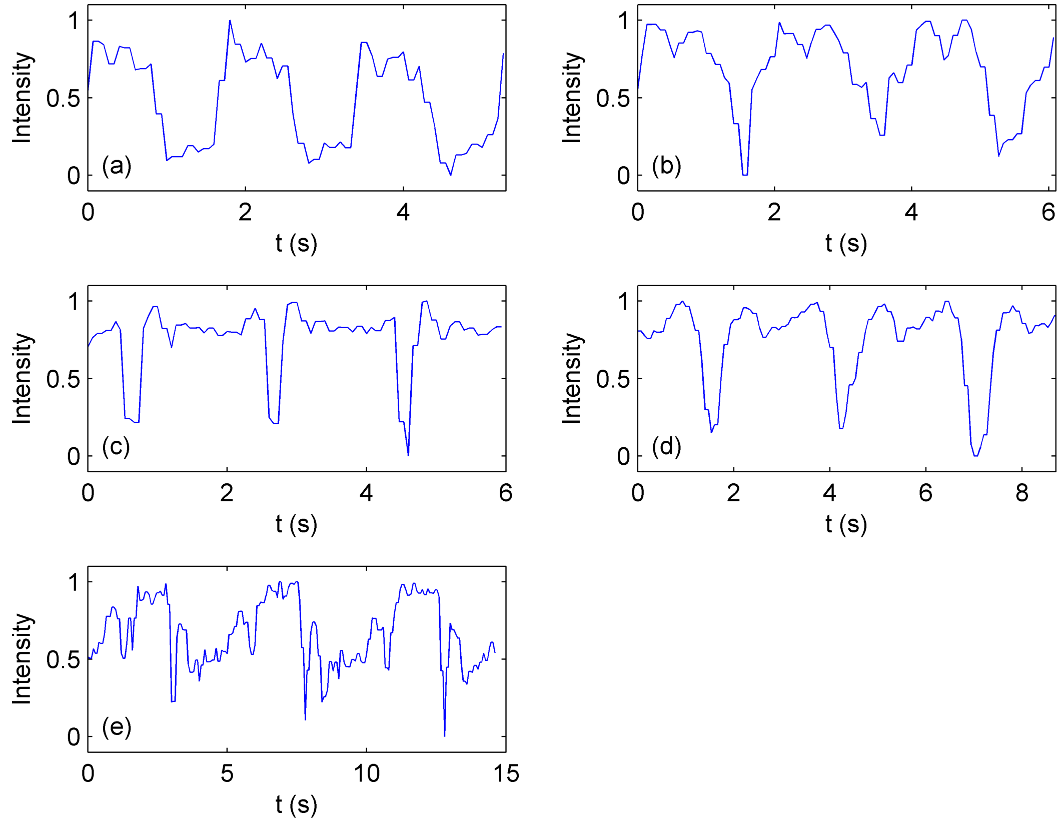

Figure 3. Time-varying FMG signals acquired by the thigh transducer. Performed actions comprise (a) walking in place, (b) marching, (c) jumping, (d) crouching, and (e) sitting/standing up from a chair.

Despite its merits, decoding complex motions requires additional transducers to discriminate the response of individual lower limb joints and correct ambiguities due to ankle movement or intentional contractions. One observes that the force levels vary for standing and sitting volunteers, demanding a reference signal to circumvent such issues. Furthermore, designing portable interrogation hardware is recommended once the fiber cables may obstruct the user's movements. Possible solutions include single-board computer-based systems, as proposed in previous works.[7]

4. CONCLUSION

This proof-of-concept study demonstrated an optical fiber FMG sensor for evaluating lower limb motions. A single transducer attached to the thigh muscles attained 5.4° resolution in knee joint assessment and characterized five in-place movements. Besides improving sensor robustness and repeatability, future developments will focus on integrating the FMG sensor into a robotic exoskeleton to envisage rehabilitation and action reinforcement in human-robot cooperation.

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