Gait Phase Detection Using 3D-Printed Piezoelectric Force Myography Sensors

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***Abstract*—Muscle activity can be utilized to detect a user's movement intention in human-machine interactions. Electromyography (EMG) is the prevalent method to assess muscle activity but has critical disadvantages in its practical implementation, particularly for long-term measurements, which are required in wearable devices. Force myography (FMG) offers an alternative approach, mechanically detecting muscle contractions by assessing the tissue deformation. Highly sensitive ferroelectrets qualify for detecting subtle muscle movements using FMG. We propose to attach individual ferroelectret sensor patches superficially to the muscle bellies, thereby avoiding crosstalk from other muscles. The sensors are additively manufactured using polypropylene, which allows for application-specific customizations. In order to investigate the suitability of these sensors for FMG during walking, we conduct a study with seven unimpaired participants. Heel strike and toe-off events are determined from the data of four leg muscles, while the ground reaction force provided by an instrumented treadmill serves as a reference. Tibialis anterior (TA) and vastus medialis (VM) suit best for determining toe-off and heel strike events, with small deviations of 3.3% ± 1.7% for toe-off detection at the TA and -1.2% ± 1.2% for heel strike detection at the VM. The experimental results demonstrate the suitability of our ferroelectret sensors as a possible substitute for EMG, underscoring their potential in assistive devices such as exoskeletons and prostheses.**

***Index Terms*—ferroelectret, piezoelectric sensor, force myography, muscle activity, smart wearable, gait event detection**

I. INTRODUCTION

Accurate interpretation of the human motion intent is crucial for human-machine interaction in the fields of rehabilitation, prosthetics, and exoskeletons [1]. In order to detect this intent, motion analysis is employed, encompassing kinematics, kinetics, and physiological signals. Muscle activity, a key physiological indicator, can be measured through various technologies, each offering distinct advantages and limitations [2]. Electromyography (EMG) analyzes bioelectrical signals from muscle action potentials. Other methods assess the resulting mechanical muscle contractions, muscle oxygenation, or blood volume changes. Ultimately, the choice of technology depends on the specific application requirements.

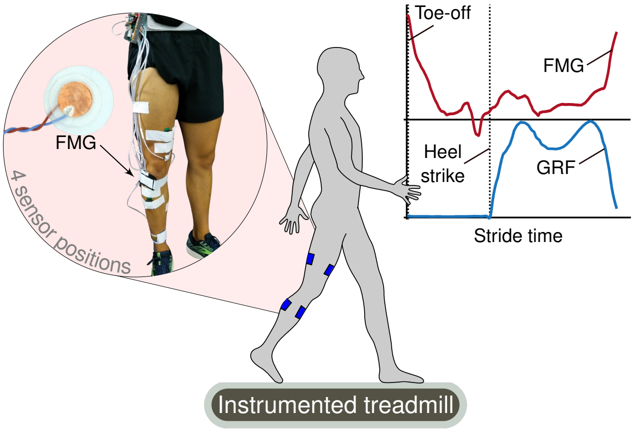

Fig. 1: Wearable ferroelectret sensors for force myography (FMG). Sensors are placed on four muscles of the right leg (vastus medialis, biceps femoris, tibialis anterior, and gastrocnemius medialis) to detect the gait events heel strike and toe-off. Reference gait events are obtained from ground reaction forces (GRFs) measured by an instrumented treadmill.

Mechanomyography (MMG) and force myography (FMG) are two techniques used to quantify a muscle's activity based on its mechanical response. MMG measures the mechanical vibrations caused by the activation of individual muscle fibers and is considered the direct mechanical counterpart of EMG [3]. Although MMG is suitable for isometric muscle activity acquisition [4], it is prone to disturbances during dynamic exercising. MMG is often acquired by using accelerometers and compared to references such as EMG [4]–[6]. FMG, on the other hand, acquires the overall deformation or pressure due to muscle contraction. While MMG and FMG signals both convey components from one another that are difficult to distinguish, we define MMG as containing mainly spectral parts in the range of EMG signals ($>10\,\mathrm{Hz}$) and FMG to resemble the spectrum around the human movement frequency ($<10\,\mathrm{Hz}$).

Despite the electromechanical delay present in all mechanical acquisition technologies, which is the time between the propagation of motor unit action potential and the corresponding mechanical muscle contraction [7], mechanical muscle activity detection offers certain advantages over EMG. In general, mechanical sensors are less susceptible to power-line interference, sweating, and inaccurate placement compared to EMG [2]. Therefore, mechanical acquisition methods, such as

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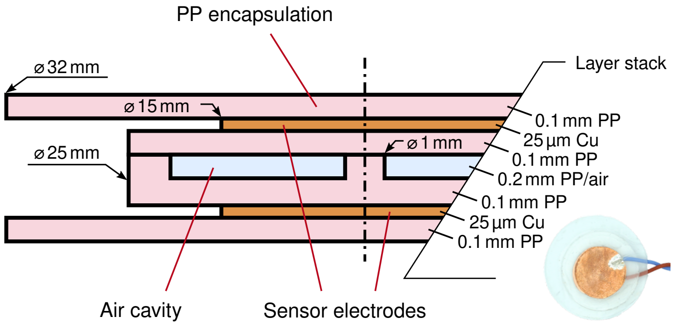

Fig. 2: Cross-section of the ferroelectret sensor design for force myography. All polypropylene (PP) parts are additively manufactured. Adhesive copper (Cu) foil serves as sensor electrodes. The sensor element is encapsulated by two circular PP parts, which are thermally fused at the outer circumference. For enhanced simplicity, the encapsulation is illustrated as plane layers.

MMG and FMG, are promising alternatives or complements to EMG for the measurement of muscle activity.

FMG is well-established for upper limb movements and gesture recognition [8]–[10], but less explored in lower limb applications [11]. Lower limb studies typically use force-sensing resistors in elastic straps around the thigh [12]–[16] or ankle [17], [18]. Alternative technologies include optical [19], [20], capacitive [21], and piezoelectric [22]–[24] sensors, with some approaches directly integrating sensors into textiles [25], [26]. However, these methods often capture muscle activity from the entire limb circumference. This crosstalk limits their ability to isolate specific muscle activities during complex lower limb movements.

Individually attached sensors are better suited to detect smaller muscle deformations than strap-based systems due to lower skin prestress. Given their dynamic working principle, piezoelectric sensors need significantly less activation pressure compared to resistive and capacitive sensors. Ferroelectrets are specifically treated, highly sensitive piezoelectric sensors, making them well-suited for measuring these subtle muscle deformations [9], [27]–[29]. Our research indicates that these sensors can detect certain movements earlier than EMG, such as in sit-to-stand transitions [30]. Moreover, our FMG sensors often demonstrate lower variability compared to corresponding EMG signals [31]. Based on these findings, we propose attaching ferroelectret (FE) sensor patches superficially to lower limb muscles for FMG-based muscle activity monitoring to detect gait events and the resulting phases (Fig. 1).

II. METHODOLOGY

The FE sensor elements are designed using CAD software (Fusion 360, Autodesk, San Francisco, CA, USA) and 3D-printed (Prusa MK3S, Prusa Research, Prague, CZ) using standard settings with commercial polypropylene (PP) filament (Centaur PP Natural, Formfutura, Nijmegen, NL). Each circular sensor element has a diameter of 25 mm and includes a 0.2-mm-thick spacing layer (Fig. 2). During the 3D-printing process, the spacing layer with a height of 0.2 mm and a width of 1 mm is 3D-printed directly onto the bottom layer. Afterward, a second circular PP layer is thermally fused onto the structure via heat pressing, forming well-defined air cavities [32]. Self-adhesive copper tape with a diameter of 15 mm serves as electrodes. The sensor is polarized via contact charging by applying a DC voltage of 5 kV between the electrodes for 3 min, using the same setup as previously described [33], [34]. For encapsulation, the sensor element is enclosed by two circular PP parts, which are thermally fused at the outer circumference.

We use a custom measurement board [35] to acquire the data of our FE sensors, which are connected to the electronics via shielded wires. The FE sensors are placed on four muscles of the thigh and shank, i.e., vastus medialis (VM), biceps femoris (BF), tibialis anterior (TA), and gastrocnemius medialis (GA). These muscles have proven to be most suitable in our previous FMG experiments. In order to apply the sensors, they are attached to the skin as patches with adhesive, non-elastic medical tape (Leukotape classic, BSN medical, Hamburg, DE). Placement of the FMG patches on the muscles closely follows the SENIAM recommendations [36].

The study is conducted with seven participants (3 female, 4 male, 24 ± 3 years, 77 ± 20 kg, 177 ± 10 cm). It has received a positive vote from the Ethics Committee of Technische Universität Darmstadt (EK 36/2022). The participants are informed about the study procedure and provide written consent prior to the experiment. During the experiment, participants walk on an instrumented treadmill (ADAL 3D-WR, HEF Tecmachine, Andrézieux-Bouthéon, FR) at $1.3\,\mathrm{m\,s^{-1}}$ for 3 min, while we record FE sensor data and ground reaction force (GRF) data as reference for gait event detection (Fig. 1).

In order to analyze the data, strides are segmented based on the toe-off events and normalized to a time range of 0 to 100%. Toe-off and heel strike events are determined by applying a 20-N threshold to the vertical GRF. All characteristic extrema of the FE sensor signals are considered landmarks. The time differences between these landmarks and the toe-off and heel strike events, respectively, are calculated for each individual stride.

From these results, the landmarks with the smallest time difference are selected for further analysis. Afterward, the muscle with the lowest variability in time differences across all trials is determined. The mean and standard deviation over all strides are individually calculated for each participant. In addition, the mean and standard deviation of all strides are determined across all seven participants to assess the generalizability of the results.

III. RESULTS AND DISCUSSION

Analyzing the FMG sensor signals reveals that the TA sensor is best suited for toe-off detection (Fig. 3, top row). In particular, the TA sensor exhibits a clear maximum, which correlates with the beginning of the swing phase. This distinct feature exists across all individual strides of all participants. For the exemplary participant P_6, the TA sensor peak indicates the toe-off event 2.7% ± 0.7% after the GRF reference (Fig. 3a). An earlier detection may be achieved by taking advantage of

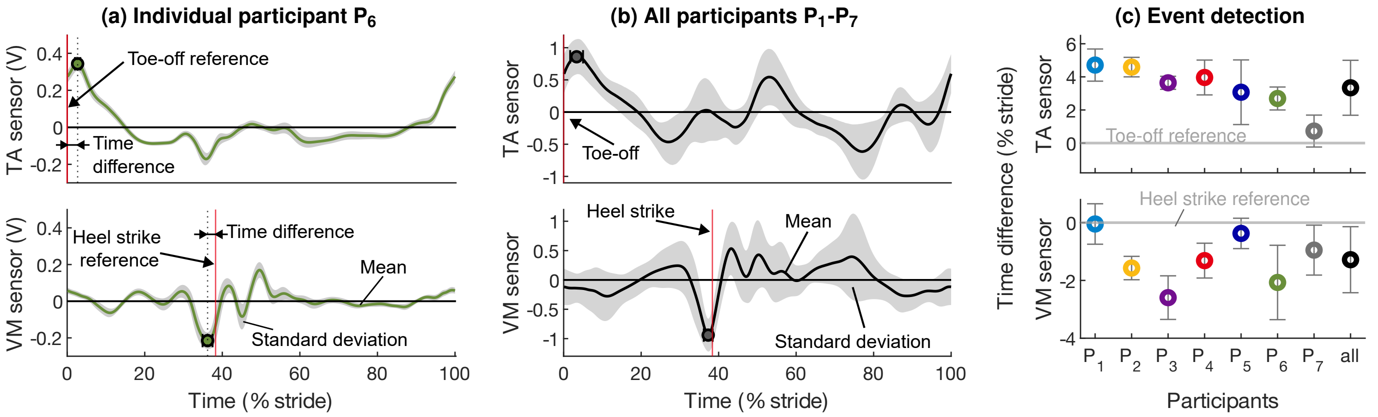

Fig. 3: Force myography (FMG) signals measured by ferroelectret sensors placed on the muscles tibialis anterior (TA) and vastus medialis (VM). The extrema show low variability and are suitable for detecting toe-off (0% and 100%) and heel strike (around 40%) events. (a) The stride-to-stride variability for each individual participant is exceptionally low, as demonstrated by participant P_6, who has one of the highest variabilities. (b) FMG signals aggregated across all participants, normalized to the maximum absolute value of each participant's mean. (c) Time differences between the ferroelectret-based event detection and the instrumented treadmill reference.

the pronounced rising edge before the peak. Heel strikes are detected best by the VM sensor (Fig. 3, bottom row). The beginning of the stance phase can be detected by the minimum in the VM sensor signal, which occurs at $37\% \pm 1.5\%$ right before the heel strike (Fig. 3a).

The sensor signals exhibit small stride-to-stride variability, in particular when analyzing individual participants (Fig. 3a). The variability of all strides aggregated across all participants is larger compared to the variability within the data of the individual participants, as we expected due to natural differences in gait characteristics. The aggregated variability is $3.3\% \pm 1.7\%$ for toe-off detection at the TA and $-1.2\% \pm 1.2\%$ for heel strikes detected by the VM sensor (Fig. 3b). Despite the slightly differing signal patterns across participants, the distinct extrema for gait phase detection exist in all acquired strides. Therefore, a simple threshold method is sufficient for the detection of these features across all participants.

For five out of seven participants, the toe-off detection exhibits standard deviations below 1% of stride time (Fig. 3c). It should be noted that the stride time normalization with respect to the toe-off can lead to slight deviations, as the individual heel strike events may not align with each other due to a natural variability in the individual gait cycles. This ambiguity may suggest larger variability than is actually present, while the heel strike and toe-off detections demonstrate similar performance across participants.

We observe no crosstalk between muscles for our individual sensor patches, as it can be seen for elastic straps in the literature [15]. However, in our future work, we aim to conduct a detailed cross-correlation analysis to substantiate this qualitative observation. Although we only present the results of two muscles in this paper, the data from the other muscles exhibit distinct features for gait event detection as well. In future experiments, we will investigate the reliability of our sensors, including the effects of sweating and mechanical stress during prolonged periods of usage. A further next step may be to use state charts, labeling the gait phases and evaluating the detection performance [18], [37]. Processing the FMG data with a machine learning approach may additionally improve gait phase detection and enable GRF estimation.

IV. CONCLUSION

In this work, we demonstrated highly sensitive force myography sensors for gait event detection based on ferroelectrets. Integrated into patches, these flexible sensors are easily applied to the skin and are intended to reduce crosstalk from other movements around the leg circumference. 3D printing allows customized sensor designs for specific applications. We extract characteristic landmarks from the recorded data and demonstrate a correlation to the ground reaction force reference. Among the muscles considered, tibialis anterior and vastus medialis have proven to be most suitable for gait event detection using force myography. The ferroelectret sensors presented require less complex preparation compared to electromyography, making them a promising candidate for supplementing or replacing electromyography measurements. Ultimately, these advantages hold potential to advance sensor solutions in rehabilitation, prosthetics, and other evolving assistive technologies.

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