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Spatiotemporally Synchronized Surface EMG and Ultrasonography Measurement Using a Flexible and Low-Profile EMG Electrode

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Abstract— **The temporally synchronized recording of muscle activity and fascicle dynamics is essential in understanding the neurophysiology of human motor control which could promote developments of effective rehabilitation strategies and assistive technologies. Surface electromyography (sEMG) and ultrasonography provide easy-to-use, low-cost, and noninvasive modalities to assess muscle activity and fascicle dynamics, and have been widely used in both clinical and lab settings. However, due to size of these sensors and limited skin surface area, it is extremely challenging to collect data from a muscle of interest in a spatially as well as temporally synchronized manner. Here, we introduce a low-cost, noninvasive flexible electrode that provides high quality sEMG recording, while also enabling spatiotemporally synchronized ultrasonography recordings. The proposed method was verified by comparing ultrasonography of a phantom and a tibialis anterior (TA) muscle during dorsiflexion and plantarflexion with and without the electrode acutely placed under an ultrasound probe. Our results show no significant artifact in ultrasonography from both the phantom and TA fascicle strains due to the presence of the electrode, demonstrating the capability of spatiotemporally synchronized sEMG and ultrasonography recording.**

I. INTRODUCTION

Human motor control is executed by the bi-directional neural signaling between the central nervous system (CNS) and human skeletal muscles. The CNS receives afferent signals, or proprioception, from the peripheral nervous system (PNS) corresponding to the limb motions and loads that are predominantly mediated by mechanoreceptors within muscle-tendon units [1]. This is made possible by mechanoneural transduction triggered by muscle fascicle forces and strains due to the nature of direct muscular actuation of articular joints. Further, to sustain the sensitivity of mechanoreceptors across a wide range of dynamic motions, the gains of afferent signaling to given mechanoneural transduction are adjusted based on its own muscle activity level along with the activities of its antagonists [2]. Based on musculotendinous proprioception, the efficient and stable efferent signaling from the CNS to lower-extremity muscles is made to meet the biomechanical requirements of targeted locomotion. Another crucial factor that, not unexpectedly, adds complexity to human motor control is highly nonlinear properties of muscular force production. The muscular force dynamics for a given muscle activity level is largely varied between isometric, concentric, and eccentric muscle contractions as well as a muscle length that it operates at [3]. Thus, it is essential to investigate both the muscle activity level and fascicle dynamics of interest through a temporally synchronized manner to fully characterize the neuromuscular system. Understanding of the neurophysiology behind human motor control could shed light on the development of effective rehabilitation strategies and the assisitve technologies.

Electromyography (EMG), which is a measurement of action potential propagation through muscle fibers, are generally used as a representation of muscle activity in both clinical and lab settings. Amongst various sensor modalities for EMG recording, surface EMG (sEMG) through surface electrodes provides, compared to other modalities such as needle electrodes or implantable electrodes, a relatively easy-to-use and noninvasive recording of muscle activity and, hence, has been widely used in the field of rehabilitation, biomechanics, neuroscience, and kinesiology [4]. On the other hand, ultrasonography provides easy-to-visualize, noninvasive, cost-effective measurements for muscle fascicle dynamics [5]. Ultrasonography has been successful in characterizing individual muscle architecture and has been used for both clinical and research applications such as the development of computational musculature models, assistive robotic control, and gait abnormality detection. However, obtaining spatiotemporally synchronized sEMG and ultrasonography for the muscle of interest is often challenging due to the nature of noninvasive sensor modalities, in which both the surface electrodes and ultrasound probe need to be placed on the targeted muscle within a limited skin surface area, and is practically impossible when the sufficient surface area to the size of the muscle is not viable due to subject's pathology, e.g., limb amputation.

Several attempts have been made to acquire synchronized sEMG and ultrasonography measurements for clinical and research applications. A few studies placed sEMG electrodes adjacent to an ultrasound probe on the skin surface for synchronous measurements; these approaches however acquire biosignals on spatially different locations on the skin, which increases risk of picking up cross-talk from surrounding muscles and, thereby, result in incoherent measurements [6]–[8]. Other studies presented special types of electrodes made of silicon rubber or hydrogel-based material [9], [10]. Although these acoustically-matched electrodes enabled spa-

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tiotemporally synchronized measurement successfully, these electrodes require complex and sophisticated fabrication processes which limits accessibility to the technologies.

In this paper, we present a spatiotemporally synchronized sEMG and ultrasonography measurement method with a flexible sEMG electrode that is easily manufacturable in a large scale with generic flexible printed-circuit-board (fPCB) manufacturing technology [11]. We demonstrate that the flexible and low profile sEMG electrode is compatible with commercially available off-the-shelf (COTS) ultrasonography equipment measuring B-mode ultrasound images. The proposed method was verified by the qualitative and quantitative evaluations of ultrasound images on a phantom and tibialis anterior (TA) muscle fascicle of a human subject during dynamic ankle motions with and without use of the sEMG electrode.

The paper is organized as follows: Section II introduces the sensor modality for spatiotemporally synchronized sEMG and ultrasonography and experiment procedures for the verification of the proposed method. The experiment results and efficacy of the proposed sensor modality is demonstrated in Section III. Finally, we detail the potential of the proposed sensor modality as an easy-to-use, low-cost, and noninvasive measurement of muscle activity and fascicle dynamics and future work in Section IV.

II. METHODS

A. Flexible electrode for spatiotemporally synchronized sEMG and ultrasonography recording

In this work, a custom-made flexible and low-profile sEMG electrode, initially designed for sEMG acquisition of a residual limb within a prosthetic socket and liner developed by our group previously [11], was utilized to explore a novel sensor modality for spatiotemporally synchonized sEMG and ultrasonogrpahy measurement. This recently developed electrode consists of a Polyimide film substrate with gold plated skin-contact surfaces with a thickness of 80 to 100 micron as shown in Fig. 1. The electrode was designed to ensure light-weight, easy-to-use, and comfort of subjects while enabling large scale manufacturing with generic flexible printed-circuit-board (fPCB) fabrication techniques at a low-cost [11], [12].

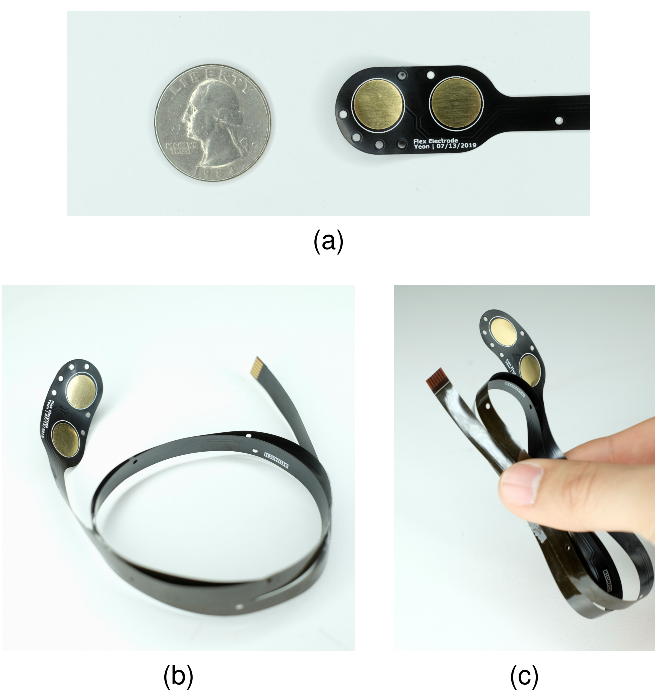


Fig. 1. Fabricated prototype of the novel electrode. (1a) Size comparison of the electrode. (1b, 1c) Demonstration of manufactured electrode flexibility. Recreated from [11] with permission ©2021 IEEE.

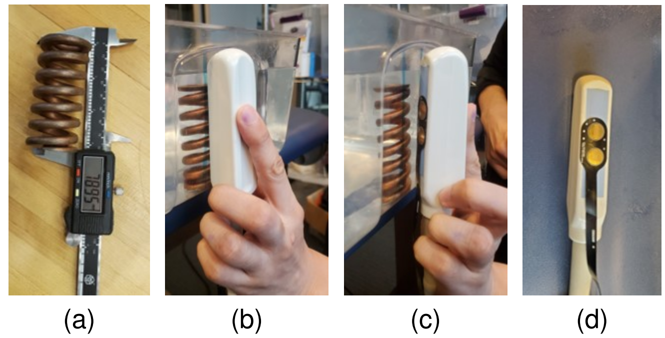


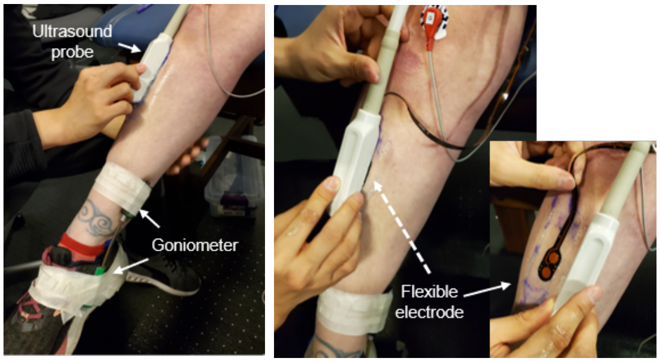
Fig. 2. Experimental setup for the validation of the proposed method through the phantom. (2a) The phantom used for the validation. (2b, 2c) Measurements of the phantom with and without the proposed electrode. (2d) The spatially synchronized electrode with the ultrasound probe.

B. Evaluation of artifacts using ultrasonography of a phantom from a flexible electrode

We first evaluated the quality of an ultrasound image of a phantom acquired from an ultrasonic probe spatially overlapped with the flexible sEMG electrode. A copper spring (length of 78.9 mm, outer diameter of 35.6 mm, inner diameter of 20.1 mm, and a pitch of 11.56 mm) was utilized as the phantom for the evaluation as shown in Fig. 2. The ultrasonograpy of the phantom was conducted by placing the phantom in the middle of a flat square plastic container filled with water while locating the ultrasound probe on the plastic container wall with ultrasound gel. Two-types of ultrasonography (B-mode images) of the phantom, with (w EMG) and without (w/o EMG) the overlapped sEMG electrode, were collected to evaluate artifact in ultrasonography due to the presence of the electrode. Quality of the collected images were then compared to analyze an ultrasonic artifact caused by the overlapped sEMG electrode with the probe.

C. Spatiotemporally synchronized sEMG and ultrasonography recording of human muscle

We further validated the proposed method through recording spatiotemporally synchronized sEMG and ultrasonography of the tibialis anterior (TA) muscle during full ankle dorsiflexion and plantarflexion. A subject with biologically intact limbs was asked to fully dorsiflex and plantarflex the ankle while joint kinematics were recorded through a goniometer attached to medial aspect of the ankle joint as shown in Fig. 3. The ultrasound probe was acutely placed on



(a) (b)

Fig. 3. Experimental setup for validation of the proposed method through assessments of TA muscle dynamic movements. (3a) Sensor placements. The goniometer and ultrasound probe were placed on the medial aspect of the ankle joint and muscle belly of the TA, respectively. (3b) The flexible electrode was placed under the ultrasound probe, enabling spatiotemporally synchronized sEMG and ultrasonography recording.

the muscle belly the TA to assess muscle fascicle strains. Two types of trials were conducted; the ultrasonography of the TA was recorded with and without the flexible electrode placed under the probe (Fig. 3) and muscle fascicle strains were computed from the recorded ultrasound videos [13]. The subject was guided verbally to perform steady and consistent dorsiflexion and plantarflexion. Further, the placement of ultrasound probe was marked to ensure consistent ultrasound probe placements between trials. All experiments were carried out with informed consent at the Massachusetts Institute of Technology (MIT), under the approval of the Committee on the Use of Humans as Experimental Subjects (COUHES).

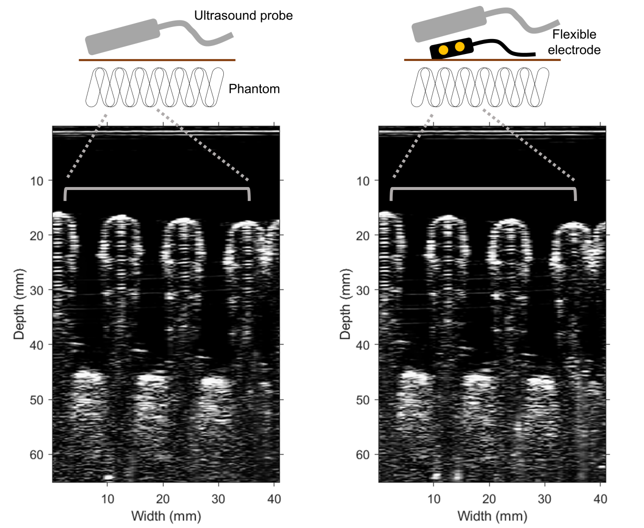
III. RESULTS

A. Artifact in ultrasonography of the phantom from the flexible electrode

The ultrasonography of the phantom with and without the flexible electrode placed on the ultrasound probe is shown in Fig. 4. To assess the quality of ultrasonography, the average ultrasonographic images with 600 frames of the phantom with and without the flexible electrode were computed. Based on the our qualitative assessments of the both images, we found no significant artifact in the image due to the presence of the electrode. Further, the ultrasonography was able to capture the features of the phantom, in which the outer diameter of spring and distance between rings were respectively 35.6 mm and 11.53 mm, while having the electrode under the ultrasound probe.

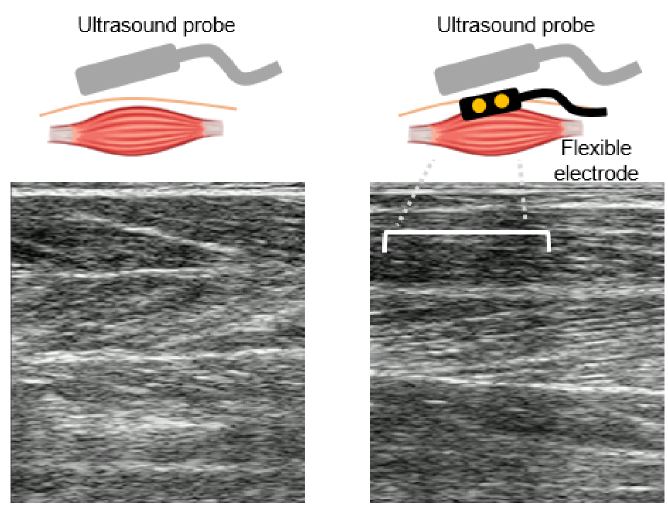
B. Spatiotemporally synchronized sEMG and ultrasonography recording of human muscle

Experimental results of spatiotemporally synchronized sEMG and ultrasonography recording of the TA muscle are shown in Fig. 5. Based on the qualitative evaluation of ultrasonographic images with and without spatially synchronized electrodes, the results showed no significant artifact induced by the presence of the proposed electrode and only marginal 'shade-like' artifact was introduced to the images. Estimated TA muscle fascicle strains from ultrasound videos were shown in Fig. 6 along with the temporally synchronized joint kinematics and sEMG. During steady full range of ankle dorsiflexion and plantarflexion, the recorded TA muscle fascicle strains with simultaneous sEMG recording showed comparable and consistent values to the fascicle data recorded without simultaneous sEMG recording. To quantify the capability of simultaneous sEMG and ultrasonography, the relationships between ankle joint kinematics and TA



(a) (b)

Fig. 4. Qualitative evaluation in ultrasonography of a phantom. (4a) Result with the flexible electrode. (4b) Result with the flexible electrode.



(a) (b)

Fig. 5. Artifact in ultrasonography of the TA muscle due to the flexible electrode placed under the ultrasound probe. Only negligible artifact is introduced in the ultrasonography as a form of shade by the presence of the flexible electrode. (5a) Ultrasonogrpahy of the TA muscle without the flexible electrode. (5b) Ultrasonography of the TA muscle with the flexible electrode.

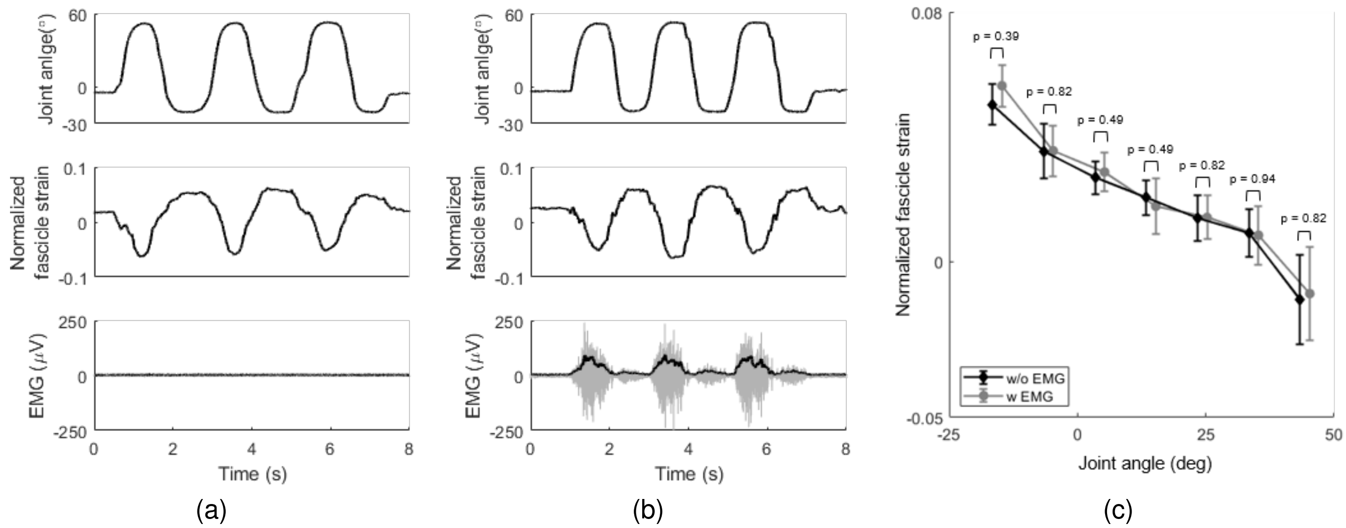


Fig. 6. Experimental results of spatiotemporally synchronized electromyography and ultrasonography recording of the TA muscle. (6a) and (6b) are representative recordings of ankle joint angle and normalized fascicle length of the TA msucle during full dorsiflexion and plantarflexion with and without EMG recording from the muscle, respectively. (6c) Joint angle and normalized fascicle length relationships investigated without (w/o EMG) and with (w EMG) simultaneous EMG recordings during full dorsiflexion and plantarflexion (n=6 cycles). No significant differences were found between the two relationship curves. P values are reported. Wilcoxon signed-rank test at a significance level of α =0.05.

muscle strains with (w EMG) and without (w/o EMG) simultaneous sEMG recording have been investigated (Fig. 6c). The similarity of the two identified relationships was evaluated by a Wilcoxon signed-rank test at a significance level of $\alpha = 0.05$ across the range of motion (ROM) as shown in Fig. 6c. Our results indicated no significant differences between the ROM in the muscle fascicle relationship to joint kinematics identified from ultrasonography with stable simultaneous sEMG recording (Fig. 6b) and the one without sEMG recording.

IV. DISCUSSION

Throughout this work, we have verified a novel sensor modality that enables spatiotemporally synchronized electromyography and ultrasonography recording. This is made possible through a flexible sEMG electrode that has only a 80-to-100 microns thickness which minimizes the interference of mechanical impedance between an ultrasound probe and the skin surface, having the electrode invisible and only leaving marginal 'shade-like' artifact in the images. For muscles with a slim-shape, small size, or that are squeezed between other muscles, it is extremely challenging to obtain temporally synchronized sEMG and ultrasonography recordings due to limited surface area allowed for the muscle of interest. Generally, placing the sEMG electrode aside to ultrasound probe, or non-spatially synchronized electrode placement, is not preferred because of high cross-talk in sEMG recording from surrounding muscles, making it difficult to estimate the muscle activity level of interest. With conventional surface electrodes for sEMG recording such as a Ag/Cl electrode, it is arguably impossible to collect ultrasonography data while placing the electrode under the probe due to the volume of the electrode and its significant artifact in the images. Nevertheless, by simply placing the flexible electrode under the ultrasound probe along with the conventional ultrasound gel, the proposed sensor modality was able to obtain temporally synchronized sEMG and ultrasonography with minimal surface area, offering the capability to study a wide range of musculature in a noninvasive manner.

In developing a musculoskeletal model towards implementing biomimetic assistive technologies and establishing effective rehabilitation, identifying muscle fascicle relationship against the joint kinematics is critical. The experiment results show that the proposed sensor modality provides non-inferior ultrasound imaging of muscle fascicle dynamics while also providing stable sEMG recording. This would allow the design of sophisticated musculoskeletal models with detailed descriptions of muscles based on the directly measured, temporally synchronized muscle activity and muscle fascicle data. Moreover, this would offer the opportunity to further verify and develop our understanding of afferent-efferent signaling and reflex, which is known to be mediated by both the fascicle dynamics and activity level of muscle, in an in vivo setting.

Meanwhile, utilizing spatial sEMG data collected from high density grid (HD-sEMG) electrodes to estimate multi-modal physiological information has emerged as an active area of investigation [14]–[17]. By simultaneously considering the additional data from ultrasound imaging along with HD-sEMG data collected from flexible HD-sEMG electrodes fabricated with our proposed approach, we envision the potential to capture high-resolution, synchronous mechanical and electrical muscle dynamics that provide new insights into muscle neurophysiology.

The proposed sensor modality poses as a easy-to-use, low-cost, and noninvasive measurement of spatiotemporally synchronized sEMG and ultrasonography. Future works will include the development of a musculoskeletal model and investigation of neural circuitry behind complex motor control based on the spatiotemporally synchronized sEMG and ultrasonography measurements. We hope that this work will enable more research on accurate modeling of human biomechanics through the proposed multi-modal measurement method.

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