Quantification Of Stretch Reflex Using A Multi-modal Sensing Device: Device Development and Pilot Human Study

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INTRODUCTION: Although stretch reflex tests are non-invasive, quick, and inexpensive, they remain highly subjective and qualitative. A reflex is an involuntary response to stimulation and involves multiple components, including the muscle spindle, sensory neurons, spinal cord, motor neurons, and the target muscle. The condition of any one of these components can influence the characteristics of the reflex, which are difficult to assess without advanced technologies. To address this, various studies have attempted to quantify reflexes using tools such as force transducers, accelerometers, motion analysis systems, and electromyography (EMG). While these methods have provided valuable insights, they present two key limitations. First, these techniques rely on indirect signals like muscle electrical activity or body movement. Such indirect approaches can introduce inaccuracies in measuring the intensity or timing of the reflex. Second, timing measurements in these studies typically begin at the moment of hammer impact. However, the true onset of the reflex arc occurs when the impact wave reaches the muscle spindles. Ignoring this delay can distort both timing and intensity measurements. Moreover, the propagation of the hammer impact wave through the body is significantly influenced by the mechanical properties and condition of the muscle-tendon complex. To overcome these limitations, we propose an acoustic sensing system capable of capturing both the mechanical wave generated by the hammer impact and the resulting muscle contraction. This system not only allows for direct measurement of muscle contraction but also provides insight into the condition of the muscle-tendon complex based on the characteristics of wave propagation.

METHODS: We developed a multi-modal device composed of three main components: (1) a Queen Square reflex hammer with an embedded sensor to precisely measure the force and timing of stimulation; (2) an acoustic wearable that detects the mechanical manifestation of muscle activity; and (3) an EMG system to detect the electrical activation of muscles. This multimodal device provides comprehensive information regarding various aspects of the reflex arc (see Figure a). The performance of the proposed device was validated using high-speed camera imaging and digital image correlation (DIC) techniques on five healthy subjects. We tested 30 healthy subjects (16 females, 14 males; ages 24–74) with no history of neurological disorders, peripheral neuropathy, or diabetes. Each subject participated in three separate testing sessions, during which both the Achilles and patellar reflexes were assessed using the proposed device. The system output includes the EMG signal, which represents the electrical activity of the muscle, and the averaged acoustic signal, which reflects mechanical changes within the muscle (see Figure b1, b2). These mechanical changes result from the impact response with normal and transverse components as well as from muscle contraction. Six time-related parameters are used to evaluate the reflex arc: time of normal impact, time of transverse impact, EMG onset, contraction start, contraction peak, and contraction end. These parameters are used to generate a benchmark dataset to facilitate comparisons in future studies of balance impairments across orthopedic, neurological, and other clinically relevant conditions.

RESULTS SECTION: High-speed camera imaging with digital image correlation validated five of the six extracted parameters, with errors below 9.8%. The EMG timing was not validated through imaging but was confirmed based on manufacturer specifications. Each parameter corresponds to a distinct physiological or mechanical event occurring in sequence during the reflex response. Testing on 30 healthy subjects demonstrated that the proposed system can reliably capture the ordered sequence of reflex events. The transverse and normal waves represent the mechanical responses generated by the hammer impact that activate the muscle spindles. Owing to its propagation characteristics, the normal wave reaches the spindle earlier, initiating the sensory signal, which is then transmitted to the spinal cord. This is followed by the generation of the motor signal and its transmission back to the muscle, reflected in the onset of the EMG. Subsequently, muscle contraction begins, reaches a peak, and then relaxes to baseline. Except for the EMG onset, all parameters showed mean absolute percentage errors smaller than the differences in timing between adjacent events, ensuring that despite relatively high variability (standard deviation), the events remained distinguishable. These results confirm that the system is capable of quantifying the temporal sequence of reflex activity with sufficient resolution to separate each stage of the reflex arc.

DISCUSSION: This study demonstrates the feasibility of a multimodal device for objective reflex quantification by simultaneously capturing electrical and mechanical signals. Validation with high-speed imaging confirmed the accuracy of most extracted parameters, showing that distinct physiological events can be reliably separated despite inter-subject variability. While validation was limited to healthy subjects, these findings support the potential of the proposed device as a practical tool for clinical reflex assessment.

SIGNIFICANCE/CLINICAL RELEVANCE: This work establishes the feasibility of a non-invasive, quantitative approach to reflex testing that captures both neural and mechanical components of the reflex arc. The ability to objectively measure reflex timing and sequence has direct clinical relevance for detecting and monitoring balance impairments and neuromuscular disorders in orthopedic, neurological, and geriatric populations.

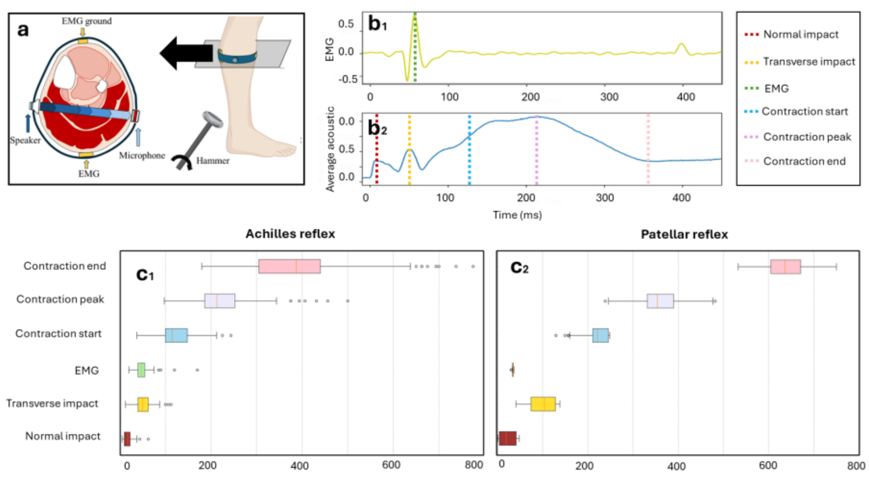

Figure 1: (a): schematics of proposed sensing system. ($b_{1,2}$) EMG and average acoustic signal measured during an Achilles reflex conducted on a healthy subject. ($c_{1,2}$) Distribution of 6 time-related parameter used to form database