Abstract—Muscle function assessment is important for diagnosing muscular disorders, developing treatment plans, and tracking patient progress over time. The muscle force assessment system (MFAS) can provide quantitative results versus the traditional qualitative results that are obtained from manual tests. A new MFAS was developed for measuring force in the tibialis anterior muscle in response to electrical stimulation. The system is small, portable, and can be used in an ICU setting. Preliminary experiments were conducted to compare the new system to an existing force assessment system. The results demonstrated that the new system is repeatable and reliable.

I. INTRODUCTION

Muscle function assessment is an important tool that is routinely used by neurologists, orthopedists, general practitioners, anesthesiologists, and occupational and physical therapists [1]. Evaluation of muscle strength is important because it is used for differential diagnosis to determine if impairment or disability is present, to decide if a patient qualifies for treatment, and to track effectiveness of a treatment. This technology is especially valuable in a clinical setting such as an intensive care unit (ICU).

Acquired neuromuscular disorders are common in patients in the ICU [2]. Standardized screening for weakness in the ICU setting is uncommon and persistent weakness as a sequel of critical illness is usually not recognized by physicians in the ICU [3]. Such muscle weakness can be caused due to muscle atrophy, a number of drugs, or due to neuromuscular disorders such as critical illness myopathy (CIM) or critical illness polyneuropathy (CIP) [2]. Since patients in the ICU generally suffer from delirium and sedation, reliable bedside examination of neuromuscular function can be difficult [4]. Attempts have been made to quantify such muscle weaknesses for diagnostic purposes and to understand underlying disease etiologies [5]. One of the main reasons for the absence of such data is that current procedures require patient cooperation which is not practical in severely ill and highly sedated ICU patients.

To overcome challenges of patient cooperation and the need for muscle biopsy and invasive methods, noninvasive surface stimulation of muscle stimulation is preferred. Activating the muscle with electrical pulses provides a known input that is not influenced by the patient, and when coupled with sensor-based recording of the output muscle force, the assessment system is objective and repeatable [1].

Systems for measuring isometric force of the tibialis anterior have long been reported. For example, the device used by Bobet et al., was effective in generating data; but requires the subject to be seated [6]. ICU patients tend to be severely ill and are generally supine. Maganaris et al. studied ankle dorsiflexion by using magnetic resonance imaging (MRI) [7]. The MRI technology is not a bedside technology for an ICU setting. Mela et al. studied the torque exerted by ankle dorsiflexor muscles. They developed a custom designed bench for subjects to sit on and to tightly strap their foot on to a foot plate [8]. The bench is large and cannot be used with critically ill patients in an ICU setting. Hoang et al., developed a similar bench technology for measuring the torque at the ankle produced by the gastrocnemius muscle, but this bench is also large and requires the patient to be prone [9].

An earlier version of a muscle force assessment device was developed by our group [10][11] and used by Ginz et al. to analyze the involuntary, isometric skeletal muscle forces of the ankle dorsiflexor muscles in the ICU [12]. This device, displayed in Figure 1, is large, heavy, and impractical for an ICU patient. The goal of this project was to develop the next generation muscle force assessment system (MFAS) that would be small, portable, light weight, and easy to don and doff. The next generation MFAS can serve as bed side technology in ICUs and can be used to produce quantitative results for controlling and optimizing physical rehabilitation therapies.

Fig. 1. Existing muscle force assessment system. ICU application shown at right.
II. DEVICE DESCRIPTION

The improved MFAS for measuring tibialis anterior force is shown in Figures 2 and 3. The foot, resting on an orthosis insert, is strapped to the bottom plate and the shank to the reaction bar. The plate is extra wide to accommodate a foot and shank with severe swelling from edema, common in ICU patients [13]. A load cell that measures joint torque resulting from muscle force is located between the shank and the reaction bar. The load cell capacity is 50 lbs, which corresponds to 34 Nm of stimulated muscle torque. (Healthy subjects produce no more than about 20 Nm of torque in response to a train of six pulses at supra-maximal current.) The ankle angle can be from 20 degrees of dorsiflexion to 45 degrees of plantar flexion and is fixed through quick release clamps on each side. A potentiometer is embedded in one of the joints to measure ankle angle. The yoke support spins freely about the main axis so that the leg can be relaxed and supported off the floor without affecting the joint torque reading. Structural components were fabricated from aluminum. The total weight is 2.4 kg and the weight without the yoke (which must be minimized so as to not interfere with the muscle response dynamics) is 1.6 kg.

Figure 4 shows the sensing and control architecture for the MFAS. A custom stimulator that delivers monophasic, transformer-coupled controlled current pulses is controlled by the host computer through a USB connection. A USB connected data acquisition board reads the load cell and potentiometer with 14 bits of resolution. The stimulator is powered by a 12 V battery and the electronics by the host computer through the USB power line. Sensors were calibrated prior to subject testing.

The MFAS system measures muscle twitch force in response to single, supra maximal stimulation pulses. Single twitches are used because they are sufficient for tracking changes in muscle force and, unlike a continuous contraction with a train of supra maximal forces, twitches can be tolerated by subjects. Further, the muscle twitch response is not affected by reflexes, which could be an issue for subjects with spasticity. Table 1 and Figure 5 illustrate the parameters of interest, which include peak torque, contraction time, torque-time integral, start time, half peak width, half decay time, and inter-pulse interval.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Torque (PT)</td>
<td>Highest torque attained by the twitch.</td>
</tr>
<tr>
<td>Torque-Time Integral (TTI)</td>
<td>Area under the twitch torque curve from 10% of peak to 25% of peak.</td>
</tr>
<tr>
<td>Start Time (ST)</td>
<td>Stim to 5% of peak.</td>
</tr>
<tr>
<td>Contraction Time (CT)</td>
<td>Time from 5% of peak to 100% of peak.</td>
</tr>
<tr>
<td>Half Peak Width (HPW)</td>
<td>Width of twitch at half peak amplitude.</td>
</tr>
<tr>
<td>Half Decay Time (HDT)</td>
<td>Peak to 50% of peak.</td>
</tr>
<tr>
<td>Inter-Pulse Interval (IPI)</td>
<td>Time between two pulses</td>
</tr>
</tbody>
</table>
Device evaluation testing was conducted on healthy male and female human subjects with no previous or current muscle disease. Subjects were screened using an inclusion-exclusion questionnaire along with their informed consent to participate in the experiments. The study was approved by the University of Minnesota Institutional Review Board (IRB).

The subject was strapped into the MFAS and the tibialis anterior (TA) muscle was stimulated using 1.5"x 2.0" oval, self-stick surface electrodes. Stimulation was applied as single pulses spaced by about 1 s to measure the muscle twitch response.

Twitch force was sampled at 1000 Hz for 500 ms starting at the stimulus pulse. Knowledge of muscle force as a function of joint angle is used in some clinical studies so for some tests, the subject’s TA was stimulated at the maximum amplitude for 3 pulses at various angles. The subject’s leg was first held in a 0° position. The 0° position corresponds to the foot and leg at a 90° angle. Three pulses spaced by one second were applied at that position, and the data was stored. This process was repeated for several angles. Data analysis was performed using a custom function written in MATLAB, which averaged the responses for the three pulses.

Figure 6 shows typical twitch force results from one subject for several angles. Figure 7 demonstrates that the apparatus produces the same TA twitch force whether the knee is bent or straight. The straight knee configuration will be used in the ICU.

The mechanical natural frequency of the apparatus with foot attached was measured by impacting with a rubber mallet, and found to be 73 Hz. Test-to-test and day-to-day reliability tests were performed using three subjects. This involved repeated donning and doffing of the apparatus. The average test-to-test repeatability was 3.3% and the average day-to-day repeatability was 3.5%.

IV. DISCUSSION

The MFAS system was capable of producing clean, repeatable muscle force signals resulting from electrical stimulation. The high natural frequency, which results from designing the structure of the apparatus to be light and stiff, was 73 Hz, well above the 36 Hz of the original system shown in Figure 1. A high mechanical natural frequency is important for accurate estimation of muscle twitch dynamics.

The repeatability results demonstrated that the MFAS can be used for clinical studies that track changes in muscle force over time where the device is donned and measurements are taken daily. Because patients vary in size, shape, nominal strength and amount of fat, within subject tracking of stimulated muscle force change over time has greater utility than comparing across subjects.

The device is sufficiently small and light to be used for measuring muscle strength of a patient in the ICU. The yoke is advantageous as it enables measuring force while the subject is lying supine because the weight of the leg is supported by the yoke and does not contaminate the muscle force signal as the yoke has no moment about the ankle joint. This is particularly useful for measurements in the ICU.

REFERENCES


