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An Integrated Motion Capture System for Evaluation of Neuromuscular Disease Patients

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Abstract—**There currently exist a variety of methods for evaluating movement in patients suffering from neuromuscular diseases (NMD). These tests are primarily performed in the clinical setting and evaluated by highly trained individuals, rather than evaluating patient in their natural environments (i.e., home or school). Currently available automated motion capture modalities offer a highly accurate means of assessing general motion, but are also limited to a highly controlled setting. Recent advances in MEMS technology have introduced the possibility of robust motion capture in uncontrolled environments, while minimizing user interference with self-initiated motion, especially in weaker subjects. The goal of this study is to design and evaluate a MEMS-sensor-based system for motion capture in the NMD patient population. The highly interdisciplinary effort has led to significant progress toward the implementation of a new device, which is accurate, clinically relevant, and highly affordable.**

I. INTRODUCTION

SPINAL muscular atrophy (SMA) is a genetic motor neuron disease caused by a mutation in the SMN gene, leading to degeneration of motor neurons in the brain stem and spinal cord [1]. The disorder causes weakness and atrophy of the voluntary muscles, severely limiting the mobility and general motor skills of the patient. SMA is among the most frequent autosomal recessive diseases, with a prevalence of 1 in 6000 live born infants [2]. The major symptom of SMA, severe muscle weakness, is also a key characteristic of several other NMDs, such as Duchenne muscular dystrophy (DMD). When present in the limbs, such weakness critically limits a patient's ability to function during activities of daily living (ADLs). Despite the high incidence of such disorders, there exist few objective outcome measures for clinical research involving NMD patients, which are critical for objective evaluation of experimental treatments. For example, the most widely used measures in SMA, such as the Gross Motor Function Measure (GMFM) [3], and Hammersmith Motor Function Scale [4] all rely on a trained clinician to observe and score a patient's function. These methods introduce two significant limitations. First, evaluation of the patient typically must occur in the clinic, which restricts how often the test can be performed, as well as its ability to gauge function during true ADLs. Second, the standardized scoring techniques often lack the resolution to distinguish variations within the patient population (especially within subtypes of SMA), thereby introducing a degree of subjectivity from the observer. Various evaluation methods for other NMD populations exist, but typically exhibit similar drawbacks.

Currently available visual motion capture systems [5], [6] can track and quantify the motion of a subject with stunning accuracy and in real time. However, such systems require multiple cameras, extensive calibration, and a highly trained operator. Even simpler single-camera systems [7] have not been demonstrated outside the controlled laboratory environment. Combined with the prohibitive costs, these limitations make in-home use of such devices impossible. Other methods of motion assessment, such as electromyography (EMG) have also shown promising results in the laboratory [8]. Still, the invasive and obstructive nature of EMG signal acquisition precludes the use of such a device in the home, especially by a patient already burdened by more essential medical equipment. By harnessing the recent advances in micro-machined electromechanical systems (MEMS) sensors, several studies have demonstrated the applicability of solid-state accelerometers and gyroscopes to motion capture in healthy subjects [9], [10] as well as neuromuscular patient populations [11].

We hypothesized that a gyroscope-based motion capture system could enable routine assessment of NMD patients in their home. The small weight and size of the sensors would permit them to be worn or placed on an assistive device (such as a gravity-neutral orthosis, or GNO) without interfering with ADLs. Combined with the low power consumption of the sensors, and small bandwidth of the data, the ambulatory system could enable long-term studies of function during ADLs (Fig. 1). Furthermore, we designed a set of software modules to streamline the process of information flow between the clinic, the patients and their caretakers and quantitative evaluation of the progress of disease and patients' motion improvement as a result of device usage.

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II. METHODS

A. Design Specifications

Our initial design specifications arose from multiple interviews with neurologists, physical therapists, patients and their families. We chose to focus our design around pediatric patients suffering from Type II and III SMA, who represent a large proportion of the patients seen at the SMA Clinical Research Center, and exhibit many characteristics common to other NMDs. This selection dictated several critical features of our prototype. Our observations indicated that apart from specific exercise sessions, the majority of our patients' ADLs included various arm motions; we therefore decided to study upper-limb motion in order to attain the best representation of a patient's typical activities. Preliminary estimates of the motion indicated that the total range would be approximately 1 m along any single axis, with a maximum linear uniaxial acceleration of 9.8 m/s2. Furthermore, the weakness associated with SMA led us to impose a sensor weight limit of ≤ 100 g per limb, in order to avoid interfering with the patient's independent motion.

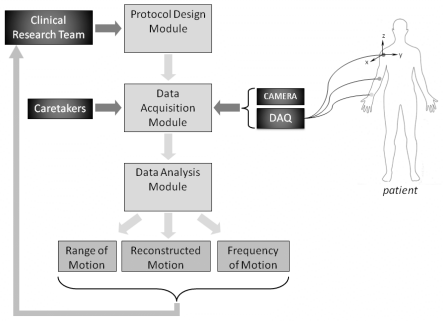

Fig 1. Diagram of proposed information flow between the clinical research team, the caretakers, and the patient.

To specifically overcome the limitations of current assessment modalities, we sought to determine which outcome measures would lend themselves to straightforward interpretation while retaining strong clinical relevance. The general consensus among the neurologists and physical therapists was that the range and frequency of motion would be the most descriptive and accessible parameters to assess. In addition, while full 3D motion capture and analysis would be the final goal, a partial 2D reconstruction was deemed acceptable for current testing purposes.

The interviews conducted with potential system users (clinicians and caretakers) indicated an average level of computer literacy. While we envisioned fairly complex graphical interfaces for testing the prototype, it became clear that the end-users ought to have access to the minimal functions required to operate the device, with advanced features reserved for highly-trained users, particularly for post-processing accumulated data sets.

Finally, we assessed the cost constraints of the system. Interviews with patient families revealed that most would be unwilling and unable to spend more than several hundred dollars on a complete system. However, the SMA Research Center could spend up to $2000 on a single device, and potentially purchase several such devices to rotate among different patients. We therefore targeted the total cost of our system to this price range.

B. Sensor selection

In the first prototype, we elected to use solid-state accelerometers (ADXL-203, Analog Devices, Norwood, MA, USA), with a range of ±1.7g and 1000 mV/g ratiometric sensitivity along each of 2 axes. These parameters represented the best balance between the predicted range of accelerations and the sensitivity required to capture fine motions.

Due to the problems described below, our current prototype no longer relies on accelerometers, but captures motion via gyroscopes. These sensors (ADXRS-300, Analog Devices, Norwood, MA, USA) output an analog voltage signal proportional to the yaw rate, up to ±300°/sec with a sensitivity of 5.0 mV/°/sec at Vs = 5.00 V.

C. Data Acquisition and Processing

All analog signals were acquired and digitized using a USB bus-powered data acquisition (DAQ) module (NI USB-6218, National Instruments, Austin, TX, USA), and stored on a portable laptop computer (Thinkpad T61, Lenovo, Morrisville, NC, USA). Signals were sampled at 200 Hz and a Chebyshev Type 1 low-pass filter with fc= 5 Hz was applied.

In the case of the accelerometer-based signals, an additional DC-block filter was implemented to remove the static (gravity) component, to focus solely on the dynamic (motion-induced) accelerations. The signal was then integrated once to derive velocity estimates and a low-value threshold was applied. A second integration produced the displacements.

Gyroscopes are insensitive to gravity, but high-pass filtering was implemented to minimize offset drift, and a single integration was used to derive angular displacement from the yaw rate.

In addition to the raw motion data, a commercial webcam provided a synchronous video record of the motion capture sessions. The initial conditions for kinematic analysis (i.e. the starting position of a patient's arms) could then be estimated from the video.

D. Software Design

Based on the design specifications, we developed three distinct software modules intended to streamline the processes of protocol creation, data acquisition and quantitative analysis (Fig. 2). The protocol design module allows a clinician to specify several parameters, such as the position of individual sensors, the session duration, and the sampling rate. The protocol is then stored in a proprietary format and later loaded for editing, or passed on to the data acquisition module.

The data acquisition model is designed for simplicity of

use, centered on commonly accepted input and output modalities. Upon loading a protocol, a body map is presented to guide sensor placement; the user verifies that all devices are connected, and recording is controlled by a standard three-button interface (record/pause/stop).

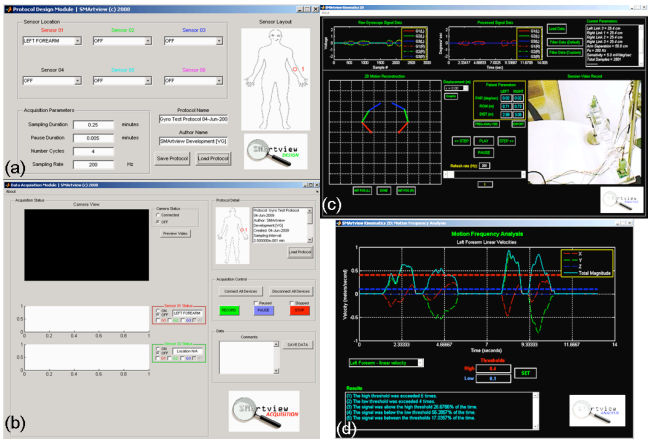

Fig 2. Images of the software modules. (a) Protocol Design, (b) Data Acquisition, (c) Motion Reconstruction, and (d) Motion Frequency. Analysis.

Additional comments are entered in a separate text field. On the left-hand side, the user is presented with visual feedback throughout the recording session. The video and digitized sensor signals are updated in real-time, allowing the user to confirm that data capture is successful. Upon completion, the compressed video and motion data are stored for offline analysis.

The data analysis module was initially developed for interpretation of accelerometer-based signals. However, with our decision to utilize gyroscopes, and following feedback on the first implementation, the module was redesigned (Fig.2(c, d)). The present version of the application permits the user to load previously captured data, apply filtering, and observe a synchronous display of the reconstructed motions and the captured video. Forward kinematics is used to derive all motion estimates, including the reconstruction and the extracted parameters (range of motion, total distance, peak rotation rate). A separate module allows a user to specify thresholds to produce frequency-of-motion estimates (e.g., to determine how often and for how long the subject's arms exceeded a certain velocity over the course of a recording session). All data acquisition and software design was performed in Matlab (Matlab R2008a, The Mathworks, Natick, MA).

E. Subjects and Protocol

For testing purposes, gyroscopes were mounted on a prototype GNO device also being developed by our group. One sensor was placed at or immediately next to each of the three points of rotation. The subject then moved his arm in the GNO while the yaw rate data was collected. To date, the device has been tested on one 18-year-old Duchenne Muscular Dystrophy (DMD) patient. The reason why a DMD, instead of SMA, patient was used was that, for the purpose of this preliminary study, adult subjects were preferred. The pool of adult neuromuscular disease subjects is, however, much more limited. During our study, consent was obtained in the case of this DMD subject. No SMA adult subjects could be recruited. However, the strength and general ability profile of this DMD patient closely mirrors that of a typical SMA Type II patient. Therefore, the study was not compromised.

III. Results

A. Accelerometer Data

Initial analysis of the accelerometer data appeared promising; the acquired acceleration waveforms correlated well with the subject's motions, and it appeared feasible to classify simple motions based on these waveforms. However, as previously reported [12], we observed two significant problems with the acquired accelerometer signals.

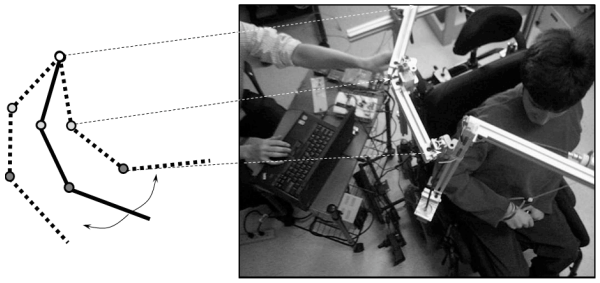

Fig 3. Placement of gyroscope sensors on the assistive GNO device during a patient trial. Each point of rotation is monitored by a separate sensor.

First, their sensitivity to gravity made it difficult to isolate the static and dynamic components due to constantly changing orientation. Second, while the acceleration data appeared stable over time, the double integration produced significant drift which overwhelmed the underlying motions. Despite the use of velocity thresholding and a variety of filtering scenarios, we observed high variability even in simple uniaxial acceleration tests. The sensitivity and range of the sensors was sufficient for recording physiological motions; occasional high-g impacts were efficiently removed from the raw signals by low-pass filtering.

B. Gyroscope Data

Analysis of data suggested that yaw rate signals provide a higher fidelity estimate of motion, with little noticeable drift over time. Several calibration tests (Fig. 4) revealed a reproducible and accurate estimation of the cumulative angle of rotation. The resultant value and error were independent of the yaw rate and total angle. However, the measured value must decrease at large distances from the axis of rotation, suggesting that a linear correction factor may be implemented. Physiological motions were also well within the range and sensitivity of these sensors.

C. Qualitative Device Evaluation

At present, we are on track to meeting the design specifications determined at the outset of the project. Based

on informal interviews with potential system users, there is already a strong acceptance of the developed software for the use of our device.

The goal of developing a lightweight and portable system has been met, as each sensor weighs < 5 g; further, the current method of attaching the sensors onto an assistive device and routing the wiring along the metal frame essentially reduces the weight to zero.

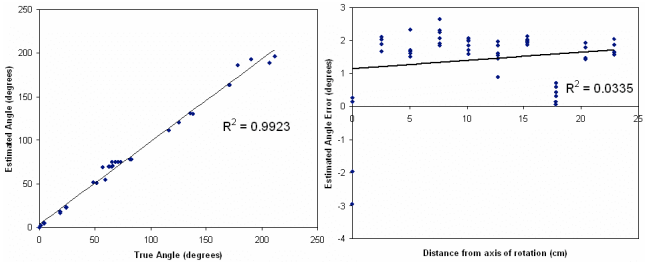

Fig 4. Gyroscope calibration results. On left, angles estimated based on gyroscope output show high correlation with true angles ($R^2 = 0.9923$). On right, at distances of < 25 cm, angle estimates appear to be independent of the distance from the axis of rotation ($R^2 = 0.0335$).

IV. Discussion

There currently exist various modalities for capture and evaluation of motion in both healthy individuals [5]–[8], [13] and patients suffering from neurological [14] and neuromuscular [15], [16] disorders. While they achieve high accuracy and hold great potential for numerous applications, they are often limited to highly controlled environments, require extensive calibration, and are not designed to be affordable. For researchers aiming to evaluate the effectiveness of new treatments for NMDs, there exist several methods of in-clinic assessment; these measures may not accurately reflect a treatment's effect on a patient, because they are not intended to assess ADLs. The goal of the present study was to develop a robust and affordable system of motion capture for routine use by NMD patients, in order to assess the effects of new interventions.

Potential users in the clinic have thus far provided positive feedback on the device. The hardware is minimally intrusive and does not interfere with self-initiated motion, especially as it is integrated with the assistive device. The software is straightforward and easy to use with minimal training.

Having ruled out the possibility of using accelerometers to directly measure motion, ongoing efforts are focused on characterizing and calibrating gyroscope sensors in order to achieve reproducible and accurate motion capture in 2D. The newly developed GNO prototype offers an ideal platform for this investigation, as it is intended to assist arm motion in the horizontal plane using 3 points of rotation.

An important effect which must be considered when using gyroscopes is the measurement of rotation not around the sensor's own axis. As shown in Fig. 4, while the gyroscopes accurately measure rotations about their own axes, they also sense rotations at a distance. However, at sufficiently large radii, incremental rotations approximate linear motion, to which these devices are insensitive. These two factors have a significant implication for the reconstruction algorithm: for some sensor locations, it is necessary to adjust the estimated angle based on the sensor's current position.

With respect to our goal of making the system affordable, we identified the portable computer and DAQ module as the most expensive components. These components will be used for ongoing system development and testing, but we foresee a significant price reduction arising from implementation of specialized components and in-house production of particular sensor circuitry.

V. Conclusion

A prototype system for robust motion capture in uncontrolled environments has been developed. The device specifications were customized based on input from a multidisciplinary team of neurologists, physical therapists, and biomedical engineers, with the goal of overcoming the limitations of existing modalities. Though many aspects of the device are still being refined, there is strong acceptance of the system by future users, and promising preliminary data with respect to the feasibility and accuracy of motion capture during usage of the device.

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