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DEVELOPMENT AND APPLICATIONS OF A SELF-CONTAINED, NON-INVASIVE EVA JOINT ANGLE AND MUSCLE FATIGUE SENSOR SYSTEM

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Abstract

The University of Maryland Space Systems Laboratory, as a participant in NASA's INSTEP program, is developing a non-invasive, self-contained sensor system which can provide quantitative measurements of joint angles and muscle fatigue in the hand and forearm. The goal of this project is to develop a system with which hand/forearm motion and fatigue metrics can be determined in various terrestrial and 0-G work environments. The work presented here is a preliminary study of the prototype sensor systems and data reduction techniques for the fatigue measurement system. The sensor systems evaluated in this study include fiberoptics, used to measure joint angle, surface electrodes, which measure the electrical signals created in muscle as it contracts; microphones, which measure the noise made by contracting muscle; and accelerometers, which measure the lateral muscle acceleration during contraction. The prototype sensor systems were used to monitor joint motion of the metacarpophalangeal joint and muscle fatigue in flexor digitorum superficialis and flexor carpi ulnaris in subjects performing gripping tasks. Subjects were asked to sustain a 60-second constant-contraction (isometric) exercise and subsequently to perform a repetitive handgripping task to failure. Comparison of the electrical and mechanical signals of the muscles during the different tasks will be used to evaluate the applicability of muscle signal measurement techniques developed for isometric contraction tasks to fatigue prediction in quasi-dynamic exercises. Potential data reduction schemes are presented.

Introduction

Localized muscle fatigue constitutes a danger in many workplaces. Excessive use of a particular muscle group can cause disabling fatigue which may compromise both the safety and productivity of a worker. This is especially true in the space environment. For example, some limitations on extra-vehicular activity (EVA) productivity can be attributed to fatigue in the muscles of the fingers and wrist.[1] Current space suit gloves do not precisely maintain constant volume during finger and wrist motions, so internal pressure tends to keep the gloves in a preferred position. The constant effort required to counteract this force causes the observed muscle fatigue.

However, existing data on this problem is largely anecdotal, and a serious effort to understand the biomechanics of muscle fatigue will require quantitative, repeatable measurements of joint motions and muscular parameters. An adequate database describing fatigue in many different work environments would allow the development of appropriate physical models, validate simulation approaches and provide a reference for evaluating new equipment.

A device to monitor fatigue should have certain characteristics.[2] The monitor should be non-invasive, and should be easy to don at the start of a work session. It must reliably provide an accurate representation of the state of muscle fatigue, and must not be affected by external electronic, mechanical, or thermal stimuli. The monitor and associated electronic hardware must be small and should not interfere with the tasks of the worker. Furthermore, the capability of the monitor as a predictive tool for fatigue must not be affected by the types of motions and tasks performed by the worker. In addition, the determination of muscle fatigue should not require measurement of forces applied to the objects on which work is being done, since this would require instrumentation of the worksite as well.

The University of Maryland Space Systems Laboratory, as a participant in NASA's INSTEP program, is developing a non-invasive, self-contained sensor system which can provide quantitative measurements of joint angles and muscle fatigue in the hands and forearms of

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astronauts performing EVA. The goal of this experiment is to develop a system with which hand/forearm motion and fatigue metrics can be determined in various terrestrial work environments. Subsequently this system can be applied to the study of extra-vehicular activity and simulations thereof in an effort to increase astronaut safety, efficiency, and probability of mission success.

These goals will be attained by instrumenting the hands and forearms of astronauts with sensors designed to measure both the pertinent joint angles and those physiologic parameters which are indicative of fatigue. Fiberoptic cables, placed along the skin's surface across a joint, provide a means to measure joint position and velocity during typical EVA activities. As a joint bends, light passing through the fiber is attenuated to a degree dependent on bend radius; the amount of attenuation can thus be used to calculate joint angle. Joint motions of interest include elbow flexion, wrist flexion/extension and supination/pronation, and flexion/extension of first (thumb) and second digits. The resulting data can be used to determine preferred hand positions and motions, and will be correlated with data describing muscle fatigue to calculate minimum-fatigue positions.

Physiologic changes associated with localized muscle fatigue are numerous and well documented. However, few methods of measuring these changes are accurate, non-invasive, and unobtrusive enough to be suitable for fatigue indication in space. The most promising non-invasive methods of fatigue determination depend on the mechanical and electrical properties of the contracting muscle fibers. Methods which can be used to determine the onset of muscular fatigue include surface electromyography, the measurement of the electrical signals created in the muscle as it prepares to contract; acoustic myography, measurement of the noise made by the muscle as it contracts; and muscle accelerometry, measurement of the lateral muscle acceleration during contraction. Time-varying frequency and amplitude characteristics of the acoustic and electrical signals produced by contracting muscles correlate well with subjective feelings of fatigue and with loss of strength during a constant-force handgripping task. Accelerometer amplitude correlates well with muscle force during contraction. Specific muscles of importance are the flexor carpi ulnaris and radialis, flexor digitorum superficialis (wrist and finger flexion), first dorsal interosseous muscle, flexor pollicis brevis (thumb-finger grip), extensor carpi ulnaris and extensor digitorum (wrist/finger extension).

Approach

Previous work conducted in the field of muscle fatigue has concentrated primarily on measurement of fatigue parameters during static contractions. However, for the purpose of on-the-job fatigue detection, near-maximal static contractions are time and energy consuming as they impose an additional burden on the worker. Thus, a method to predict fatigue during normal work-related motion is essential. However, it is difficult to measure parameters of muscle fatigue during non-isometric muscle contraction. As the muscle changes length, it thickens and moves underneath the skin. Thus, sensors on skin's surface are located over different areas and volumes of muscle during motion. Since electric and mechanical signals vary with position within the muscle, measurement of these signals is unreliable for purposes of fatigue identification.

However, with the addition of a joint angle sensor, the times during which contraction is isometric can be determined. Muscle fatigue parameters can be measured at these times, thus requiring no extra energy-demanding motions on the part of the worker. This approach is particularly adapted to EVA work, since motions in this environment tend to be slow, and typical hand motions include frequent gripping of tools or handrails.

Current research at the University of Maryland focuses on the correlation of muscle fatigue and joint motion of the hand and forearm in different EVA simulation environments. The work presented here is a preliminary study of the prototype sensor systems and data reduction techniques for the proposed fatigue measurement system. The prototype sensor system is being used to monitor joint motion and muscle fatigue in subjects performing gripping tasks in a laboratory setting. The experimental approach includes both constant-contraction (isometric) and repetitive handgripping tasks to evaluate the applicability of muscle signal measurement techniques to fatigue evaluation in both cases. This paper discusses the design of the experimental apparatus, including both the task workstation and the non-invasive and self-contained sensor/data acquisition systems, the testing process, and the proposed data reduction schemes. Raw data is presented, and methodology for determination of correlations between joint motions and muscle fatigue is established.

Experimental Procedure

Five subjects, all males between the ages of 21 and 40, volunteered for this experiment. After receiving a verbal description of the test procedure, the subjects were asked to read and sign a consent form. The subjects then completed a pre-test questionnaire which solicited information on age, handedness, weightlifting history and frequency of exercise, and general state of health.

In order to ascertain maximum fingertip grip strength, the subjects were asked to squeeze a grip mechanism connected to a load cell. The grip mechanism consisted of two vertical 1-inch diameter bars placed 3 inches apart. Subjects were asked to squeeze the grip between finger and thumb tips three times over a period of 1 minute, and the maximum voluntary fingertip grip strength was determined. Seventy-five percent of the maximum grip strength was used in the following endurance experiments.

The subjects were then seated at the test fixture where isometric and repetitive gripping tests were performed as shown in Figure 1. A fiberglass mold of the dorsal aspect of the wrist and forearm served as a hard support for the subjects' arm. Three velcro straps were used to secure the arm to the test fixture at the wrist and lower and upper forearm. The position of the mold was then adjusted relative to the pulley mechanism designed to hold the weights so that complete extension and flexion of fingers was unimpaired.

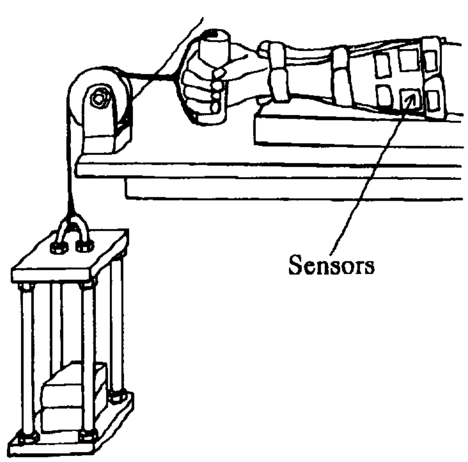

Figure 1. Experiment Setup

Flexor digitorum superficialis (FDS) and flexor carpi ulnaris (FCU) were palpated and prepared for instrumentation. The skin was cleaned with Dermasol surgical solvent (Perma-type, Plainsville, CT). Three sensors - an acoustic sensor (Radio Shack condenser microphone element model 270-090), an accelerometer (ICSensors model 3026-002-S, Milpitas, CA), and a differential electrode (Delsys model DE-02, Wellesley, MA) - were placed on each muscle. The microphone was mounted in a rigid housing designed to direct it at the arm and isolate it from external noise. The housing was attached to the arm with Perma-type brand surgical adhesive. Note that the microphone was recessed in the housing by 0.5 cm. The accelerometer and electrode were taped directly to the skin.

A fiberoptic sensor was placed along the metacarpophalangeal joint of the second (index) digit to record joint motion as shown in Figure 2. The sensor consisted of a fiberoptic cable which was etched in a small area, thus allowing light to escape from the fiber when the fiber is bent. Signal loss is therefore proportional to the bend angle. Two elastic straps, placed around the hand proximal and distal to the joint of interest, were used to fix the cable in place. The sensitive area of the fiberoptic cable was placed over the joint, and was adjusted to maximize its sensitivity for the range of motion of the joint.

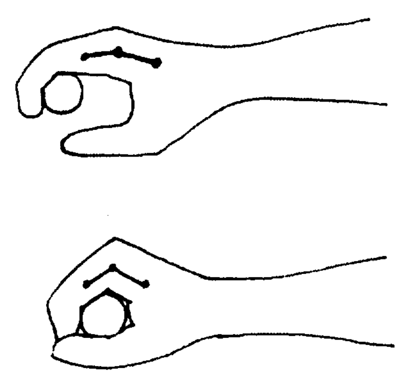

Figure 2. Fiberoptic Sensor Placement

Sensor signals were collected via a NB-MIO-16 National Instruments A/D card and a Macintosh II via Labview software. The signals were stored in data files for later examination.

Lead weight corresponding to 75% of the maximum fingertip grip strength determined previously was hung over a pulley as shown in Figure 1. Subjects were asked to hold the weight for 60 seconds. The subjects were then given a minimum of five minutes' rest, and were then asked to repeatedly curl the weight with their fingers until they were unable to do so without significant pain. Although the weight selected for the hold and curl exercises was based on fingertip grip strength and not finger curl strength, this value was selected because it resulted in 20-40 repetitions before total fatigue was experienced. The entire test session generally required 30 minutes.

Results

At the time of submission of this paper, the raw data is still being examined. Accelerometer and acoustic sensors as well as the fiberoptic angle sensor have provided acceptable traces; however the initial system used for electrode data has been unable to screen out ambient electrical noise and requires redesign. A representative 5-second interval during the curl cycle are shown for acoustic and acceleration sensors in Figures 3-5. Note that the magnitude of the signals increases with contraction; note also that the acceleration signal baseline varies as the gross muscle shape changes during each cycle.

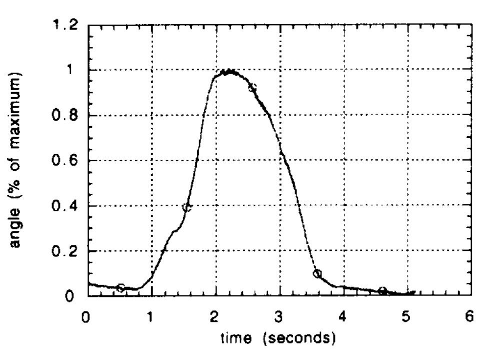

Figure 3. Grip Angle

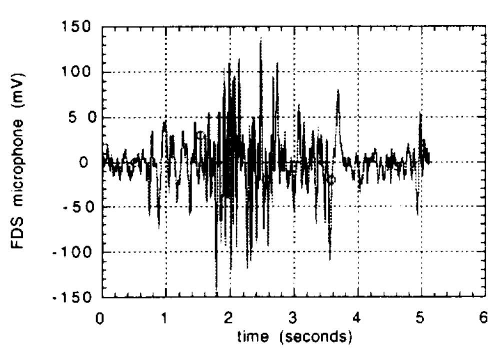

Figure 4. Acoustic Sensor Data

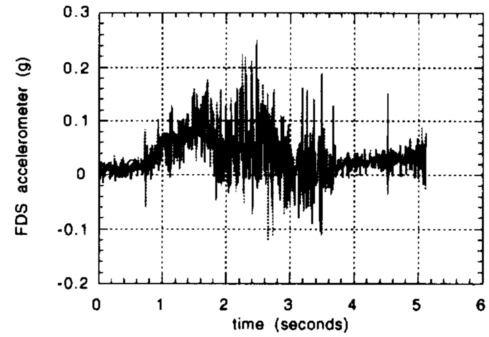

Figure 5. Accelerometer Data

Data reduction schemes are drawn from the literature. Proposed techniques include the calculation of amplitude and frequency parameters of each signal, both alone and in combination.

Electromyography

Electromyography (EMG) has been widely used to study the activation and contraction characteristics of mammalian muscle. When a muscle cell receives signals from the nerve to contract, its cell membrane becomes selectively permeable to ions. The resulting ionic shifts, which travel along the muscle fiber, can be detected at the body's surface as an electrical signal. Electrodes placed on the skin can record the composite frequency and magnitude of this signal as it is generated by many muscle fibers. Comparisons of muscle fatigue with changes in specific components of the electrical signal yield correlations of varying quality.

Numerous studies indicate that the power spectrum of the EMG signal contains information regarding muscle fatigue.[2-7] As a muscle becomes fatigued, its EMG power spectrum shifts downward, or compresses to lower frequencies. This change can be reliably monitored by tracking the mean or median power frequency of the signal. These frequencies of the power spectrum decrease linearly with time prior to loss of muscle strength; this simple relationship makes estimates of time to force loss straightforward. Furthermore, the mean power frequency recovers concomitantly with strength after a rest interval; thus it can be used to mirror recovery after fatigue bouts as well. These qualities makes frequency analysis of the power spectral density of a muscle a good candidate as a fatigue marker. Difficulties in using this method to predict fatigue include the amount of processing required to determine the power spectrum, and the need for intermittent known-force isometric contractions to acquire a stable signal. Furthermore, the EMG traces of some smaller muscles are too variable to provide adequate power spectrum information.

Accelerometry and Acoustic Myography

Acoustic myography (AMG) and muscle accelerometry detect sound waves produced by the act of muscle contraction. The pressure waves pass through the tissue and are detected either at or above the skin's surface. Both acoustic myography and accelerometry thus measure the muscle's mechanical activity. As with EMG, these signals' frequency spectra and amplitude traces have been examined to determine mechanisms of both muscle activation and fatigue.

Selected studies indicate that the amplitude of the mechanical signals correlates well with force production.[8,9] This can prove useful in determining the force-time history of the worker's muscles, and for selecting periods of relatively constant force for examination of fatigue parameters. Stable EMG signals, recorded during constant-force portions of a contraction, could be extracted for spectral analysis. Thus, the combination of accelerometer amplitude and EMG power spectrum could be used to determine fatigue without imposing additional activities on the worker.

Additional studies suggest the comparison of mechanical and electrical signal amplitudes as a means of fatigue measurement.[10] The acoustic amplitude represents the mechanical activity of the muscle fibers, while the electrical signal represents the excitation of the muscle. Changes in the relative amplitudes of these signals can be indicative of the fatigue process.

Conclusions

The goals of the Unversity of Maryland's joint angle and muscle signature (JAMS) project is to determine the joint motions and muscle fatigue in the hand and forearm of astronauts performing EVA activities. The system will be used to compare simulation environments with actual on-orbit work, to aid in the development and evaluation of advanced suit and glove designs, and to aid in the planning and definition of EVA operations. Although developed for NASA, this sensor system can be applied to people in numerous terrestrial environments. Evaluation of joint motions and muscle fatigue can be used to improve ergonomic tool design, improve task design to mimimize fatigue, or improve rehabilitation techniques to maximize recovery.

The purpose of this preliminary experiment is to validate previous fatigue measurement techniques for sustained isometric contractions and extend these techniques to quasi-dynamic exercises. A sensor system which relies on constant-force isometric contractions during normal work periods, and does not require additional fatiguing contractions for data collection, will facilitate the development of a fatigue system which is invisible to the worker.

Upon satisfactory correlation of fatigue sensor data with losses in force production (or impending losses of force production), the system will be used to monitor joint motion and muscle fatigue in subjects performing a series of representative EVA tasks. First, dry-land testing will be conducted in a 1-gravity (1-G), naked hand situation. This work will establish a baseline of fatigue data with which subsequent tests will be compared. The system will then be used to assess muscle fatigue during similar tasks performed by a subject wearing a space suit in a neutral buoyancy environment. Finally, the system will be used on-orbit during normally-scheduled EVA tasks. Comparison of fatigue in 1-G, neutral buoyancy, and on-orbit environments will provide objective data on the quality of the correlation between simulation training and microgravity activity. Current plans call for neutral buoyancy testing in March, 1995 and 0-gravity simulation testing on board NASA's KC-135 airplane in mid-late 1995.

The applications of this research are broad. The ability to measure and to predict fatigue of critical muscle groups will provide a mechanism with which safety, mission planning, and EVA suit and tool designs can be significantly enhanced. Determination of fatigue rates of workers performing specific tasks will enable mission strategists better to estimate both the time and number of workers required to fulfill a mission. Measurement of fatigue rates in different pressurized suit gloves will aid in the selection of optimal suit design. Tailoring of specific tasks and tools to reduce muscle fatigue, and alternation of tasks to allow fatigued muscle groups to recover, will aid in optimization of the overall mission profile.

Future applications of the joint angle and muscle fatigue assessment device, including whole-body or lower limb devices, are numerous. These systems could be used to determine neutral body positions (those requiring the least muscle activity to maintain) for many different workstations and tasks both in space and in conventional 1-G settings. Joint angle sensing devices placed on the arm and hand could be used to control robotic end effectors (hands), or entire manipulators, without the expense and bulk of conventional control stations.

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