Overuse syndromes of the upper extremities, often termed cumulative trauma disorders (CTDs) or repetitive strain injuries (RSIs), have been recognized as one of the foremost problems interfering with occupational performance in work (Feuerstein, 2002), in sports such as golf (McCarroll, 2001), baseball (Rizio & Uribe, 2001), tennis (Marx, Sperling, & Cordasco, 2001), and swimming (Weldon & Richardson, 2001), and in manual-wheelchair mobility (Daylan, Cardenas, & Gerard, 1999; Pentland & Twomey, 1994; Sie, Waters, Adkins, & Gellman, 1992). Upper-extremity cumulative trauma disorders are not a medical diagnosis, but a descriptive term used to designate chronic musculoskeletal pain arising from repeated use of the upper extremity over time (Zakaria, Robertson, MacDermid, Hartford, & Koval, 2002). The three main subclassifications of CTD syndromes are tendinitis/tenosynovitis (e.g., de Quervain’s, epicondylitis, rotator cuff syndromes), nerve entrapment/compression (e.g., carpal tunnel syndrome, thoracic outlet syndrome), and myofascial pain (e.g., fibromyalgia); symptoms are varied and can include weakness, discomfort, pain, swelling, limitations in motion, hyperesthesia, numbness, and stiffness (Kasch, 2002). Some CTD diagnoses, such as carpal tunnel syndrome, can be identified using specific objective tests, for example a positive Tinel’s or Phalen’s sign, decreased sensation in the distribution of the median nerve, or abnormal electrodiagnostic findings of the median nerve across the carpal tunnel. However, many conditions classified within the CTD family involve clusters of nonspecific symptoms,
often without objective evidence of an organic pathologic condition (Melhorn, 1998; Nathan & Meadows, 2002). Researchers and clinicians from a broad range of disciplines have utilized models incorporating psychosocial, musculoskeletal, biomechanical, and central nervous system variables in an attempt to come to a definitive understanding of the mechanisms underlying these complex soft tissue pain disorders (Byl & Melnick, 1997; Feuerstein, 2002; Hauffler, Feuerstein, & Huang, 2000; Huang, Feuerstein, Kop, Schor, & Arroyo, 2003; Ranney, 1997).

Worldwide, occupational therapists have played a significant role in management of upper-extremity overuse syndromes, particularly in the field of work-related injury (Folger & Jacobs, 1991; Pratt & Jacobs, 1997). In addition to evaluating and treating functional deficits of the upper extremities, occupational therapists also analyze tasks, applying anthropometric and ergonomic principles to determine motions that could be contributing to repetitive strain. Occupational therapists then design job, task or workstation modifications, recommend adaptive or assistive tools or equipment, and also provide education and training in adaptive performance techniques, as a means of controlling symptoms and preventing further injury in their clients.

High biomechanical exposure (repetitive and strain-inducing motions) and time pressure have been identified as key factors in the etiology of both upper-extremity and lower-back overuse syndromes (Huang, Feuerstein, Kop, Schor, & Arroyo, 2003). A logical next step in research is the investigation of the relationship between muscle fatigue and the onset of repetitive strain injury (Sjogaard & Sogaard, 1998).

A technology that provides objective measurement of changing muscle physiology associated with fatigue is power spectrum (or spectral) analysis of the surface electromyographic signal. As a muscle fatigues, the median frequency of the power spectrum decreases, and then increases upon recovery. The decrease in median frequency coincides with an increase in low-frequency components of the electromyographic signal, as a byproduct of the biochemical events that occur during muscle fatigue. A steeper negative median frequency slope indicates more rapid fatigue. Power spectrum analysis has been used to record muscle fatigue in lumbar extensor muscles (Basmajian & DeLuca, 1985), enabling researchers to establish a link between increased fatigability and low-back pain (De Luca, 1993; Oddsson et al., 1997; Roy & Oddsson, 1998; Roy et al., 1997). Though steps have been made to establish methodology to measure spectral parameters in the upper extremities, the link between muscular fatigue and upper-extremity repetitive motion disorders has yet to be established (Krivickas, Taylor, Maniari, Mascha, & Reismann, 1998; Merletti, Roy, Kupa, Roatta, & Granata, 1999; Moritani & Muro, 1987). Objective authentication of fatigue in muscles of the upper extremity could ultimately provide evidence to support the need for and benefit of the above services that occupational therapists offer.

This study is the pilot phase of an ongoing research project designed to develop a viable approach to the study of muscular fatigue in the upper extremities using surface electromyography (SEMG). The goal of the larger study is to improve our understanding of how fatigue and muscle imbalance might play a role in the development of a broad array of upper-extremity overuse syndromes. The shoulder of manual-wheelchair users with spinal cord injury was selected for study because of the high prevalence of shoulder pain disorders (up to 78%) in this population (Curtis, et al., 1999; Daylan et al., 1999), and the cyclic and repetitive nature of the wheelchair-propulsion task that lends itself to an isometric methodology. Several investigators of the biomechanics of wheelchair propulsion have implicated fatigue and muscle imbalance due to overuse in the pathogenesis of upper-extremity pain disorders in manual-wheelchair users (Burnham, May, Nelson, Steadward, & Reid, 1993; Powers, Newsam, Gronley, Fontaine, & Perry, 1994; Smith, Weiss, & Lehmkuhl, 1996). Intramuscular electromyographic analysis of muscle activity during dynamic wheelchair propulsion on a wheelchair ergometer indeed demonstrates that the shoulder rotator cuff muscles in particular are at risk (Mulroy, Gronley, Newsam, & Perry, 1996).

The primary aim of this study was to develop a testing protocol for gathering and analyzing shoulder muscle SEMG data during a sustained submaximal isometric wheelchair-propulsion effort, as the SEMG spectral technique requires that muscle length remain fixed. The method of power spectrum analysis was modeled on the approach of researchers with relevant techniques adapted to a study of the upper extremities (Basmajian & DeLuca, 1985; De Luca, 1993; Roy et al., 1997). A second method of analyzing the SEMG signal, called percent of maximum voluntary contraction (MVC), was utilized as well. Percent of MVC is the relative magnitude of a muscle’s contraction compared to its maximum. This analysis procedure, called normalization, allows quantitative comparison of different muscles. Percent of MVC data may be useful in attributing significance to results of power spectrum analysis, as muscles working at a high percent of their maximum will likely fatigue more rapidly (Basmajian & DeLuca, 1985; Kumar & Mital, 1996).

This pilot study sought to answer three research questions. First, will the pattern of muscle recruitment demonstrated using SEMG be consistent with the pattern of recruitment shown in previous intramuscular EMG studies of muscles of the shoulder during dynamic wheelchair propulsion? Second, is this surface electromyographic analysis system capable of capturing the median frequency shift, or fatigue slope, in the surface electromyographic data? Finally, will the data reflect differences between wheelchair users with upper-extremity pain and able-bodied controls?

Method

Surface electromyographic signals from six muscles of the right shoulder were recorded during a submaximal isometric manual-wheelchair propulsion task for two groups of participants, able-bodied and manual-wheelchair users with spinal cord injury. The signals were later analyzed to compare percent of maximal voluntary contraction and spectral parameter in the two groups.
Participants

A convenience sample of 14 male-bodied individuals and seven male manual-wheelchair users with spinal cord injury participated in this pilot study. The latter were participants in community-oriented programs sponsored by a large rehabilitation center. All were recruited via word-of-mouth. Criteria for inclusion in the study for this group were spinal cord injury at C7 or below of at least 1-year duration, customary use of a manual wheelchair, age between 18 and 60 years, and otherwise good general health. Independent review board approval for use of human subjects and informed consent were obtained.

Mean age of the manual-wheelchair user participants was 35 years (SD = 6.6) and mean time in a wheelchair was 14.2 years (SD = 9.3). Level of spinal cord injury ranged from C7 to L5 and all but one had incomplete injuries. All participants were active manual-wheelchair users and engaged in wheelchair sports as a leisure activity, with an average participation of 6.7 hours per week (SD = 4.9). Five participants were employed. All had some current upper-extremity pain; four considered their pain to be functionally limiting.

The researchers were not able to locate wheelchair users without upper-extremity pain from the subject pool available for the pilot study. Therefore, able-bodied participants were recruited from the community to serve as a comparison group. The able-bodied group had an age range of 26 to 48 years with a mean of 36 years (SD = 9.33) and no current shoulder problems. All participants were English-speaking and righthand dominant.

Instrumentation

The analysis system consisted of SEMG detection electrodes, SEMG hardware and software, and an apparatus constructed specifically for the project to guide the participant in generating a controlled submaximal isometric wheelchair-propulsion force. The 8-channel telemetered SEMG recording system (TeleMyo) with analysis software (MyoResearch) were supplied by Noraxon USA, Inc. (Scottsdale, Arizona). Electrode type and placement, skin preparation and the SEMG setup and procedure followed established protocols (Basmajian & DeLuca, 1985; Cram & Kasman, 1998; DeLuca, 1993; Kumar & Mital, 1996; Oddsson et al., 1997; Roy & Oddsson, 1998; Roy et al., 1997).

The test chair was a Quickie brand (Sunrise Medical, Longmont, CO) with an 18-inch wide seat. The frame was mounted on a secure base with locking casters that raised the wheels 1 inch off the ground so they could turn freely. Static backward force was applied to the wheels via weights suspended from an A-frame situated behind the wheelchair. Two sets of pulleys were used to transfer the force from the suspended weights tangential to the top-dead center of each wheel (see Figure 1). The right wheel was also equipped with a modified axle that could be fitted into the cylinder of the BTE Work Simulator (Baltimore Therapeutic Equipment Company, Hanover, Maryland), a computer-controlled resistance recording and generating mechanism that was used to measure maximum isometric torque output at the wheelchair axle.

Procedure

Each study participant was greeted and oriented by the primary investigator. A paper and pencil demographics questionnaire was completed. Participants answered questions about general health, current activity levels and upper-extremity pain history. A physical therapist or occupational therapist performed a clinical examination of the right upper extremity, including passive and active joint range of motion, muscle strength, and 10 specific tests for shoulder impingement syndromes (Magee, 1992). Four wheelchair users were positive for shoulder impingement on four or more tests; these were also the participants who described their pain as functionally limiting.

Skin of the right upper quadrant over the muscles to be recorded was prepped and adhesive electrodes were applied. SEMG data were collected for six shoulder muscles shown in previous studies to be active during the push phase of wheelchair propulsion (Mulroy et al., 1996; Van der Helm & Veeger, 1996). These were: anterior deltoid, sternal pectoralis major, lower serratus anterior, supraspacular site (upper trapezius and supraspinatus), infraspinatus, and biceps brachii. At the supraspacular site, the specific target was the supraspinatus muscle. As the upper and middle trapezius and posterior deltoid were inactive in these studies during the push phase of wheelchair propulsion, isolation of the supraspinatus signal with a surface electrode during a sustained wheelchair pushing effort was assumed possible.

Figure 1. Design of the pulley system.
The participant then transferred to the test wheelchair. Positioning was adjusted so the angle of the elbows with the hands at top-dead center on the wheels was 110°. The top dead center position is preferential for testing of this type (Mulroy et al., 1996; Van der Helm & Veeger, 1996). A strap around the chest helped ensure trunk stability in the test chair. First, maximum torque output capability of each participant was recorded in order to determine the appropriate load for subsequent testing. The right axle of the chair was fitted to the BTE cylinder, and the participant was instructed to grip the wheels and push forward with maximum force for 5 seconds as if attempting to propel the wheelchair up a steep incline. Maximum isometric torque generated by the participant for three successive efforts separated by a 15-second rest was recorded and averaged. Average torque was divided by the wheel’s radius to determine the maximum load the participant could resist. Then, a load equivalent to 60% of maximum was chosen for the sustained submaximal effort. In the spectral technique, testing must be conducted at 60% to 80% of the muscle’s maximum (Basmajian & DeLuca, 1985).

Next, manual muscle testing was used to record the maximum voluntary contraction for each muscle using standard procedures for a sitting participant (Kendall & McCreary, 1993). Lead wires from the SEMG transmitter were then attached to the adhesive electrodes. The participant exerted three successive 5-second maximum efforts for each muscle test, separated by a rest period of 30 seconds while SEMG was recorded; he was then allowed 3 minutes’ rest prior to the sustained isometric wheelchair-propulsion effort.

Finally, for the sustained effort wheelchair propulsion test, the wheels were locked into position using the wheelchair brakes and the appropriate weight (rounded to the nearest 2.5 pounds) was loaded onto the pulley system in the A-frame. The participant gripped the wheels, the wheelchair brakes were released, and he was instructed to maintain his hold on the wheels as long as possible and to signal when he was no longer able to maintain the wheels in position. On the participant’s signal, the wheels were locked. SEMG was recorded throughout the sustained effort. When testing was complete, the participant was disconnected from the EMG, electrodes were removed and the skin cleansed, and the test wheelchair was vacated. Before leaving the testing site, the participant was debriefed and paid a monetary compensation.

Data Analysis
The MyoResearch SEMG software was used to compute the median frequency shift during the sustained effort. A regression line representing the rate of decline in median frequency for each muscle during the sustained effort was calculated. In addition, the ratio of the average amplitude for each muscle during the sustained effort to the stored maximum for the same muscle was calculated and expressed as a percent, yielding the percent of maximum voluntary contraction (MVC) values.

Descriptive statistics were generated for duration of sustained effort and load. Then the main effect for the able-bodied versus manual-wheelchair user groups was evaluated using the SPSS general linear model repeated measures design. This parametric test would be acceptable to look for patterning in a pilot study with a small N of 7 versus 14 participants. Separate analyses were run for percent of MVC and median frequency (fatigue) slope. Mean scores and standard deviations were graphed for visual image.

Results
Based on t testing, there was no statistically significant difference (p = .54) in mean load in pounds between the able-bodied (Mean = 33, SD = 7.7) and wheelchair (Mean = 31, SD = 6.6) groups. Mean difference in duration of effort in seconds between able-bodied (Mean = 126, SD = 20.4) and wheelchair users (Mean = 115, SD = 24.5) was not statistically significant (p = .30). Duration of effort did not correlate with load (r = .19, p = .40). Wheelchair-using participants reported that the sustained effort did not exacerbate upper-extremity pain.

As anticipated, all muscles selected for study were activated during the sustained effort. Infraspinatus and serratus anterior showed the lowest average amplitude of 100 to 200 microvolts in the raw SEMG signal across participants. By contrast, the other four muscles yielded average amplitudes of 300 to 800 microvolts.

A fatigue slope of –0.02 or greater was seen in 81% to 95% of all participants for anterior deltoid, supraspinatus site, infraspinatus, and serratus anterior. Only 71% of participants showed a fatigue slope for sternal pectoralis major and 52% for biceps, suggesting that these muscles were less likely to fatigue. In addition, the characteristic median frequency shift profile was evident in power spectrum analyses taken at the beginning and end of the sustained effort. A representative display of a pronounced negative median frequency slope is seen in Figure 2A. Each bar depicts a power spectrum analysis of 2 seconds of recorded SEMG for the right suprascapular site during the sustained effort. The regression line illustrates a fatigue slope of –0.8347. In Figure 2B the power spectrum display for the first and last 2-second segments illustrates the median frequency shift. No relationship could be established between median frequency slope and percent of maximum voluntary contraction.

For the main effect of average percent of maximum voluntary contraction (see Figure 3), there was a significant difference between the able-bodied and wheelchair groups (p < .05), with the able-bodied participants overall using a higher percent of MVC in this task. The graph, which depicts means and standard deviations, suggests that the main effect was derived from selected sites, namely anterior deltoid, infraspinatus, serratus anterior, and sternal pectoralis major. The main effect of median frequency slope showed a trend (p < .10) whereby the able-bodied were in general more fatigued than the wheelchair users (see Figure 4).

Discussion
This pilot study represents the beginning phase of research in an important investigative pathway that could ultimately provide objective, reliable and valid evidence to document upper-extremity muscle fatigue during cyclical, repetitive functional activities. The characteristic linear negative median frequency slope seen in the majority of
subjects was consistent with other studies associating this surface EMG finding with muscle fatigue in the low back during sustained submaximal isometric contraction (Basmajian & DeLuca, 1985; DeLuca, 1993; Oddsson et al., 1997; Roy & Oddsson, 1998; Roy et al., 1997). The pattern of muscle activation, as evidenced by recording of percent of maximum voluntary contraction, was also consistent with previous research measuring intramuscular EMG activity during wheelchair propulsion (Mulroy et al., 1996).

Because this study was preliminary, a number of unanswered questions and methodological considerations will need to be addressed in subsequent research. First, why the consistently lower amplitude for infraspinatus and serratus anterior? The problem could be technical, related to greater thickness of skin and adipose tissue and poorer quality of contact between skin and electrodes. Second, what might account for the higher percent of maximum voluntary contraction and greater fatigue slope found among able-bodied users? The answer would be purely speculative at this point. Manual-wheelchair users could have been more efficient in the way they recruited their muscles during the sustained push task. In previous research, setting the sustained effort resistance at 70% to 80% of maximum force output yielded more consistent fatigue slopes (De Luca, 1993; Oddsson et al., 1997). In the current study, participants worked at 60% of maximum. The reason for this decision was concern over exacerbating pain or causing injury in those with preexisting problems. However, the manual-wheelchair user participants with pain did not report that the static task was problematic, making increase in level of resistance worth consideration.

Third, can we assume that supraspinatus was active and the overlying upper trapezius inactive during the sustained isometric push? Previous research suggests that this would be the case (Mulroy et al., 1996; Van der Helm & Veeger, 1996). One technique in future studies would be to compare surface EMG activity at the distal suprascapular fossa and a more proximal site. If the distal site proved more active during the sustained isometric push, it would be less likely that upper trapezius was contributing significantly to the effort.

Fourth, the static trial used in this research replicated the demand in only one part of the propulsion cycle and did not look at fatigue in the recovery phase muscles, which have a longer duration of activity during the propulsion cycle with a similar intensity. Fifth, the participants were strapped across the chest during the test. This was necessary to ensure consistency in positioning and trunk stability during the static effort, but as a condition not present in real life could have introduced a confounding factor. Finally, the sample size was small and variability of percent of maximum voluntary contraction and median frequency slope was considerable. A number of factors potentially contributed to variations among participants, including: (1) a broad representation of manual-wheelchair users with differing clinical signs of shoulder impairment; (2) a nonstandardized duration for the static sustained effort, and (3) possibly insufficient recovery time between muscle testing for maximum voluntary contraction and the sustained effort.

Once methodological problems have been solved, objective evidence of changing muscle physiology associated with fatigue might be used by occupational therapists...
treating individuals with a broad array of overuse syndromes as the basis for teaching adaptive performance techniques, documenting progress, or justifying provision of assistive technology or adaptive equipment in order to maintain occupational performance. For example, of the approximately 1.5 million manual-wheelchair users in the United States (Kaye, Kang, & LaPlante, 2000), from 23% to 64% will develop an upper-extremity pain disorder secondary to wheelchair propulsion serious enough to significantly reduce functional and community mobility and interfere with occupational performance in work, play, leisure, or social participation (Daylan et al., 1999; Pentland & Twomey, 1994; Sie et al., 1992). An objective means of justifying to payers the need for assistive technology to enhance mobility, as well as documenting the positive effect of implementation of that technology, would be of great help to occupational therapists and the clients they serve. The surface EMG technologies currently available are sophisticated both in signal detection sensitivity and in analysis capability while also being “user friendly.”

The practicality of surface EMG would allow broad testing of individuals and the compilation of sufficient data to identify patterns associated with dysfunction. Applications of this surface EMG technology within occupational therapy practice can be of far-reaching benefit in supporting services offered to those with overuse syndromes.

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