Effect of Haptic Force Feedback on Upper Limb

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Abstract — **A methodology for studying the effect of vibrations generated by a haptic interface on upper limb is introduced. In the proposed methodology, a subject presses on a horizontally vibrating, rigid, virtual object with a cheap off-the-shelf (COTS) haptic device. When the subject feels vibrations of fixed amplitude and varying frequencies the electromyographic (EMG) activity of upper limb is recorded. The relationship between the maximum force feedback and the amplitude of the EMG recordings is obtained. It suggests that EMG activities in upper limb increase significantly even for small changes in the low force feedback from the haptic device. These results can be used to develop rehabilitation programs and evaluation methods that are based on vibration force feedback produced by COTS haptic devices.**

Keywords—**Electromyography, haptics, upper limb rehabilitation**

I. INTRODUCTION

Mechanical vibrations are used for rehabilitation in many countries. Vibration stimulation during strength training has recently gained popularity. Vibrations have been combined with conventional resistance training in an attempt to attain larger gains in neuromuscular performance than through conventional resistance training alone. Several experiments have demonstrated that whole-body vibrations can reduce the frequency and intensity of electromyographic (EMG) activity [1]-[6] while producing increases in muscle force similar to those produced by muscle strength training. Mechanical vibrations can also be used for pre-training warm-up. The benefit of vibrations demonstrated in these studies is that they improve muscle strength without overloading the joints. High-profile sports teams have adopted vibration stimulation during intensive weekly training to accomplish the need of athletes to enhance their competitiveness. Vibrations are used as part of the cool down routine after intense exercise and/or competition to retain the flexibility of muscles [7]. Increased efficiency of rehabilitation has also been sought through robotic assistance. Diverse approaches have led to positive outcomes [8]-[11]. Efforts have been made to develop rehabilitation systems that employ virtual forces provided by haptic interfaces [12].

This paper presents a method for rehabilitation of upper limb and preliminary experiments with healthy subjects. The proposed technique uses a cheap off-the-shelf (COTS) haptic interface to present stimulating vibrations to the subjects and records the EMG activity of upper limb muscles while the user feels the vibrations from the haptic device. The goal of the work presented is to evaluate the effectiveness of vibration feedback from COTS haptic devices for the rehabilitation of upper limb.

II. METHODOLOGY

1) Simulation of a vibrating object in virtual environment: A solid cube connected to a rigid wall through a spring has been simulated in Microsoft Visual Studio using C++ as the programming language. The dynamics of the virtual mass-spring system depicted in Figure 1 are given by

$$ma = -kx \qquad (1)$$

where a is the acceleration of the cube, m is its mass, k is the spring stiffness, and x is its position measured from the point where the spring is neither stretched nor compressed. When an impulse excitation is applied to this virtual mass-spring system, it vibrates with frequency ω given by

$$\omega = \sqrt{\frac{k}{m}} \qquad (2)$$

and measured in rad/sec.

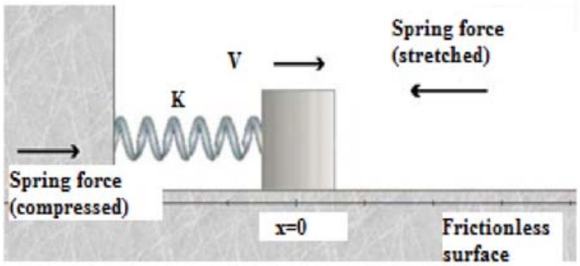

Figure 1. Mass-spring system on a frictionless surface with the mass at $x = 0$. The spring constant is k, the cube mass is m, and its initial velocity is v.

If the virtual mass-spring system is at static equilibrium when the impulse excitation is applied at time $t = 0$, we have

$$
\begin{aligned}
x(0) &= 0 \\
v(0) &= 0 \\
a(0) &= 0
\end{aligned}
\tag{3}
$$

Its evolution in time can be simulated using fixed-step forward Euler integration with the time step τ equal to the step of the force feedback loop of the haptic device. Specifically, the acceleration, initial velocity and position are given by

$$
\begin{aligned}
a_{i+1} &= -\frac{kx_{i+1}}{m} \\
v_{i+1} &= v_i + a_{i+1}\tau \\
x_{i+1} &= x_i + v_{i+1}\tau
\end{aligned}
\tag{4}
$$

2) *Surface electromyography recordings*: The EMG activities have been recorded from the anterior deltoid (AD), the posterior deltoid (PD), the biceps brachii (BB), the triceps brachii (TB), the flexor carpii radialis (FCR), and the extensor carpii ulnaris (ECU) muscles using pairs of surface electrodes positioned on each muscle belly, as shown in Figure 2. The EMG activity has been measured with Ag-AgCl surface electrodes from Thought Technologies. The electrodes have been placed in bipolar configuration with 2.5 to 3.0 cm inter-electrode distance, center to center. Ground electrodes have been placed over bony landmarks near each muscle. The skin has been prepared with isopropyl alcohol prior to electrode placement. The EMG electrode apparatus includes a reference electrode and bipolar recording electrode units. The EMG signal has been amplified using a gain of 5000, and has been stored on a personal computer with a sample rate of 1 kHz.

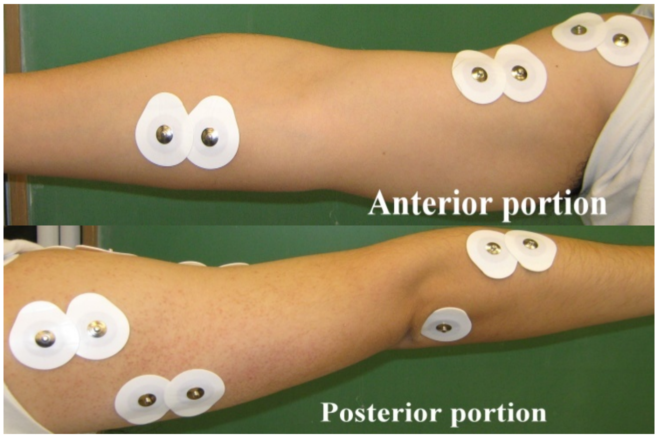

Figure 2. Placement of the EMG surface electrodes on upper limb.

3) *EMG signal processing*: The EMG signals from the surface electrodes contain artifacts. Because muscles are volume conductors and closely packed, electrical signals propagate indiscriminately through them regardless of the origin of the signal. Therefore, the EMG activity of one flexor muscle can readily be detected by electrodes placed over an adjacent flexor muscle. In this work, crosstalk is minimized by using wire electrodes that have small surface areas [13]. In addition, crosstalk artifacts are removed from the EMG recordings by using adaptive filters. The EMG signals recorded from upper limb when users touch the virtual cube at rest (i.e., without any vibration) provide the reference signal to the adaptive filter. Least-mean square (LMS) adaptive filtering has been used to remove the artifacts from the EMG signals.

4) *Experimental method:* The experiments have been conducted in the Rehabilitation Neuroscience Laboratory at the University of Victoria, Canada. Five male and two female right-handed subjects, aged 24 to 30 years, voluntarily participated in the experiment. They had no known history of neurological or muscular disorders.

The haptic interaction system comprises a FALCON NOVINT haptic device (Figure 3) and a laptop computer. The haptic interface provides three degrees of freedom (DOF) displacement sensing and force rendering and thus supports point interaction in 3 DOF virtual environments.

Figure 3. The NOVINT FALCON 3 DOF haptic device.

The position sensing and force rendering rate of the FALCON NOVINT haptic device was 1 KHz. Surface electrodes have been placed on each subject as depicted in Figure 2. The subjects held the haptic device in the fixed position (shoulder 35° flex, 20° abduct, elbow 112° flex, wrist neutral 0°) illustrated in Figure 4. A wrist brace maintains the position of the wrist fixed. In the simulation of the vibrating solid cube in the virtual environment, the stiffness of the spring k changes in steps so that the frequency of vibration of the cube with mass $m = 1\,\text{kg}$ varies. Subjects push down on the top surface of the cube in order to feel the vibration (Figure 5). For each vibration frequency, the EMG signals and the maximum force generated by the haptic device were recorded. Three trials were conducted for each frequency. Subjects rested for 30 minutes between trials to prevent muscle fatigue recordings.

The EMG recording corresponding to no cube vibration was used to remove the muscle crosstalk artifacts from the EMG signals recorded for the various frequencies of vibration using LMS adaptive filtering.

Figure 4. Position of upper limb while holding the haptic device.

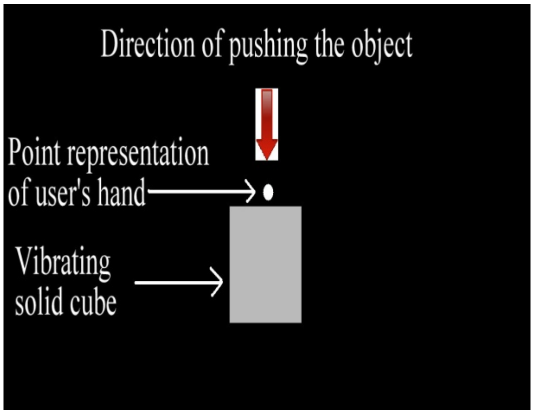

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Figure 5. The virtual environment presented to the user including the vibrating virtual cube and a point representation of the user's hand.

III. RESULTS

Figure 6 shows an example EMG signal of the AD muscle recorded while the virtual cube vibrated with a frequency of $\omega = \sqrt{300}$ rad/sec. The artifacts from the EMG signal were removed by LMS adaptive filtering and then the resultant signal was rectified as shown in Figure 7.

In this experiment, significant changes in the EMG activity of the anterior deltoid (AD) and of the extensor carpii ulnaris (ECU) muscles have been observed. The EMG activity in the other four muscles remained constant throughout the experiment for all subjects. These results can be interpreted by considering how each muscle participates in the experimental procedure. Specifically, the AD muscle causes flexion and medial rotation at the shoulder while the ECU muscle causes extension and adduction at the wrist. During the experiment, the shoulder required to be flexed and medially rotated while the wrist needed to be pronated and slightly extended to hold the haptic interface in the appropriate position. Hence, the AD and the ECU muscles needed to be active to maintain the static position of the arm.

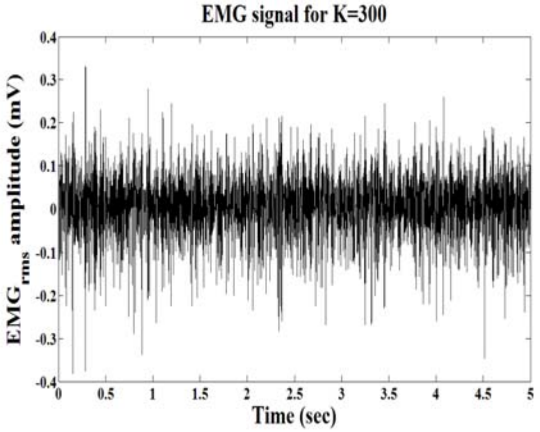

Figure 6. Sample EMG signal for K=300 (AD).

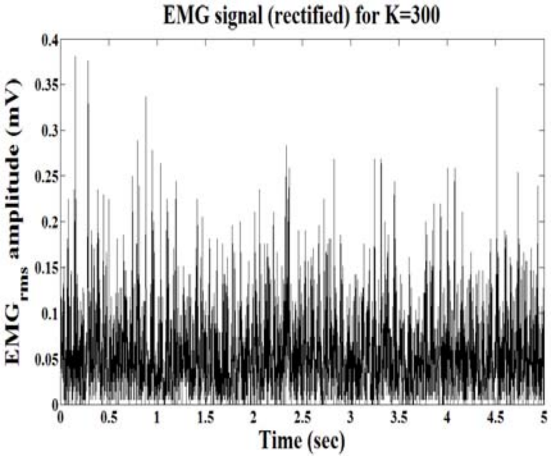

Figure 7. Sample rectified EMG signal (AD).

The experimental relationship between the maximum force feedback from the haptic device and the root mean square (rms) amplitude of the EMG signals from the AD and the ECU is curvilinear as shown in Figure 8. Although the haptic device system can provide a maximum force of up to 4 N, the EMG activities increase significantly even for smaller changes in the haptic feedback. The experimental results obtained suggest that a force feedback as small as 3 N could have a significant training effect on the AD and the ECU muscles. The evidence for the improved muscle activation pattern to assist/resist the force from the haptic device is provided by the EMG data. Furthermore, the results shown in Figure 8, which were obtained with healthy subjects, could be used as a reference to evaluate and assess subjects with various upper limb impairments.

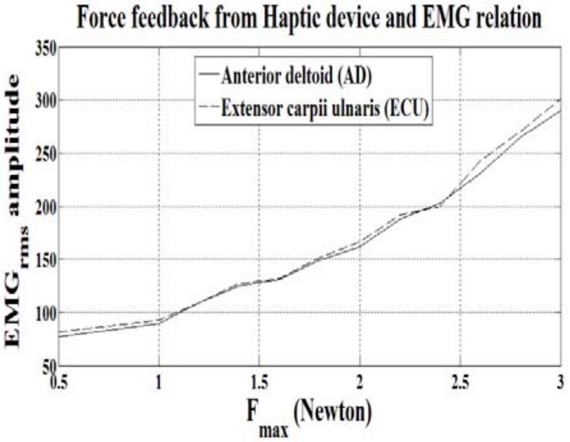

Figure 8. Typical experimental relationship between the maximum force feedback from the haptic device and the EMG of the AD and of the ECU muscles.

Upcoming work focuses on evaluating the efficacy of using vibration feedback generated by COTS haptic devices for the rehabilitation of subjects with various upper limb impairments.

IV. CONCLUSIONS

An experiment with healthy subjects has been carried out that demonstrates that a curvilinear relationship exists between the maximum force feedback from a haptic device and the rms amplitude of the EMG signal of the AD and the ECU muscles. The curvilinear relationship validates that EMG activities in upper limb can increase significantly for small changes in low haptic feedback. Hence, the experiment suggests that COTS haptic devices can be used to train and rehabilitate the AD and the ECU muscles.

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