NEW APPROACH TO MODEL THE HAND-ARM SYSTEM FOR ANALYSIS OF MUSCULOSKELETAL DISORDERS

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1. INTRODUCTION

Musculoskeletal disorder is a big part of the hand-arm vibration syndrome (HAVS) affecting millions of workers using hand-held tools. It is known that factors that cause HAVS are the magnitude and frequency of the vibration input as well as posture and gripping force (Griffin, 1990). The pathology of HAVS is still not well understood (Friden, 2001). A good hand-arm model is necessary to estimate the transmission of vibration forces through the human body, which will provide basic information to understand HAVS.

A human hand-arm system is composed of 31 different muscles has 24 degrees of freedom of motion. The system acts in combination of synergism and antagonism to generate forces required for motion. To create a higher force, muscles act synergistically along with increasing contribution of antagonistic muscles for stabilization and restoration of joint (Hatze, 1981; Prilutsky, 2000; Seireg and Arvikar, 1989). A musculo-tendon force transmission model is required to calculate forces and displacements transmitted through joints and muscle systems. Most dynamic models do not consider detailed muscle models (Rakheja et al., 2002). Such models are useful to calculate overall responses of the hand-arm system but not its internal responses. The purpose of this study is to develop a new analysis approach that takes all the above mentioned factors into account for hand-arm vibration analysis.

1.1. Muscle Model

Extrinsic muscles are actively controlled by motor neurons. A modified Hill's muscle model (Figure 1) is used to define the muscle force generation (Cheng et. al., 2000). The parameters are obtained from a similar model developed based on Simulink known as Virtual Muscle 4.0 (Song et. al., 2008). Each extrinsic muscle consists of a contractile element (CE) in parallel with passive elastic component (PE) connected to a muscle mass. The muscle mass and insertion location are connected by series elastic (SE) element which represents the tendon.

2. METHODS

Once the system parameters are found by a grip force analysis considering the active muscle force, the model of the hand-arm system can be developed which passively reacts to the tool vibration force. At a given equilibrium point, the musculo-tendon system can be interpreted as a spring damper system, as shown in Figure 2. M_1 and K_{CE1}
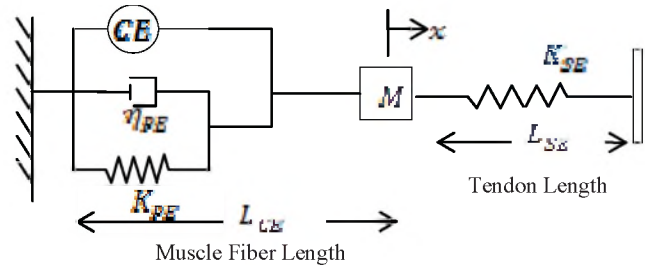

Figure 1: Modified Hill's lumped parameter based musculo-tendon system

are the mass and stiffness of the extrinsic muscle, which has bigger muscle belly. M_2 and K_{CE2} are the mass and stiffness of intrinsic muscle, which has smaller mass in comparison. Therefore, M_1 is bigger than M_2. K_{SE1} is the stiffness of the longer tendon of extrinsic muscle and K_{SE2} is the stiffness of the shorter tendon of intrinsic muscle. Therefore K_{SE1} is smaller in value than K_{SE2}. M is the mass of the segment of the finger driven by muscle and is in contact with tool, which is subjected to vibration.
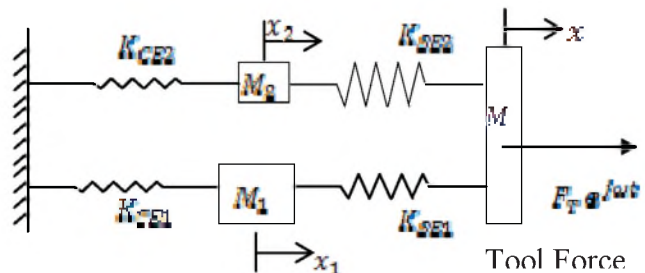

Figure 2: Schematic diagram of 3-DOF system of 2-muscles and vibrating tool

The response of the 3-DOF system can be written as in matrix form as:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F_T\} \tag{1}$$

The frequency response functions (FRF) for this system in the frequency domain are:

$$\frac{X(\omega)}{F(\omega)} = \frac{1}{-\omega^2 [M] + j\omega [C] + [K]} \tag{2}$$

And the frequency response of the velocity with force, otherwise known as the mobility, is estimated as shown below. The mobility can be used to find the contraction velocity of the muscle.

$$\frac{V(\omega)}{F(\omega)} = \frac{j\omega}{-\omega^2 [M] + j\omega [C] + [K]} \tag{3}$$

3. RESULTS

For the demonstration, a realistic human hand muscle set is used. We consider the Flexor Digitorum Profundus (FDP) and Lumbrical (LU) are participating in the response to the vibration force. Table 1 lists the properties of the muscle used in the study, where PCSA and TCSA are the muscle belly and tendon cross sectional areas. The mass of the distal finger segment in contact with tool is taken as 10g.

Table 1: Properties of the musculotendon system used (An et. al., 1979; Freivalds, 2004; Li et. al., 2001; Ward et. al., 2006)

Musculotendon	1 - FDP	2 – LU
Fiber length L_{CE} in mm	67.0 ± 6.0	47.0 ± 9.0
Tendon length L_{SE} in mm	292.6 ± 7.1	65.76
PCSA in cm^2	4.10 ± 2.40	0.30 ± 0.10
F_{max} in N	130.38	9.54
Volume in cm^3	27.6 ± 16.1	1.7 ± 0.7
Mass in g	38.82 ± 3.86	2.39
TCSA in mm^2	11.40 ± 0.97	5.0
K_{SE} in N/m	1.7922×10^4	3.4975×10^4
K_{CE} in N/m	1.86×10^3	1.345×10^2

Figure 3 shows the frequency response (X/F) of the system. It is seen that the response of the smaller muscle (lumbrical) becomes higher in the high frequency range. This indicates that smaller muscles take up most of vibration excitation in the high frequency range.
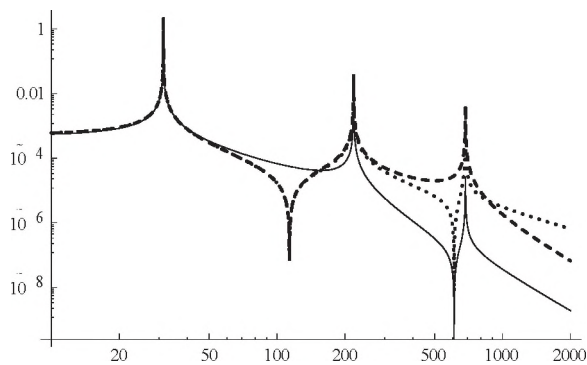

Figure 3: Frequency response functions of M (dotted line), M_1: FDP (dashed line) and M_2: LUM (solid line).

4. DISCUSSION AND CONCLUSIONS

This study shows that realistic muscle models should be included in the vibration analysis of the hand-arm exposed to tool vibration. The stiffness of extrinsic muscle has to be estimated by static analysis of grip modeling the muscle as an active element. In this study the modified Hill's model was used. Although not reported here, the hand-arm system has redundancy in muscles because it has many more muscles than the minimum number required to establish equilibrium in gripping. Therefore, the contribution of each muscle has to be determined by an optimization method.

The response of the hand-arm system to tool vibration can be considered as a passive vibration around the static equilibrium point that is set by the active muscle action. It has been demonstrated that detailed modeling of muscles is important in the response analysis. An important observation is that bigger extrinsic muscles carry most of the static load to generate the grip force: however, smaller muscles carry most tool vibration force at high frequencies.

Most experimental methods use various measurement techniques such as the electromyogram (EMG) of muscle activity to determine the muscle force generation under various dynamic conditions. But all such noninvasive measurements are only done on larger and extrinsic muscles. The current study suggests that small intrinsic muscles can be more prone to damage than simple models would predict if the vibration input has high frequency components. Thus current guidelines may underestimate the effect of high frequency vibration on possible injury.

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