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A Novel Passive Movement Method for Parameter Estimation of a Musculo-skeletal Arm Model Incorporating a Modified Hill Muscle Model

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Abstract: In this paper we present a method of parameterising a two muscle arm model incorporating a structurally identifiable modified Hill muscle model. Length and moment of inertia values were obtained by direct measurement and calculation. Spring and damping parameters in the model were determined by parameter estimation from experiments using passive flexion and extension movements. The results showed good agreement between measured and simulated data with consistent parameter values across subjects. Adding a hand load improved the agreement by reducing errors resulting from body segment geometry assumptions.

Keywords: Musculo-skeletal, Hill muscle model, joint trajectories, model, parameter estimation

1. INTRODUCTION

We have previously shown that the classical Hill muscle model (Hill, 1938) is not structurally identifiable and therefore parameter values cannot be uniquely obtained through measurement (Yu and Wilson, 2011). As part of the same study, we showed that a commonly used modified version of the Hill model consisting only of parallel elements was structurally identifiable, providing component lengths of the muscle are known.

The widely used experimental method for determining parameters values involves maximum voluntary muscle contractions (MVC) (e.g. Hoy et. al., 1990). This not only involves knowing the force-length characteristics of the muscle but if the models incorporating the modified Hill muscle model are to be applied to the design of functional electrical stimulation (FES) systems for patients with spinal cord injuries, the MVC methods cannot be used. Therefore in this paper a procedure for parameterising a mathematical model of a human arm model is described using measurements during passive movement.

2. MATERIALS

2.1 Musculoskeletal Model of the Human Arm

The two segment model shown in Fig. 1 is a representation of the human arm (Yu and Wilson, 2011). It has one degree of freedom around the elbow joint. The muscles are the flexor biceps brachii and extensor triceps brachii.

The length d_{11}, d_{12}, d_{21} and d_{22} are the distances from the centre of the joint to the points of origin and insertion of the free tendons. The free tendon is that portion of the tendon which is external to the muscle (see section 2.2). It should be noted that the lower end of the triceps wraps around the elbow when the arm is flexed. d_{arm} is the dist-

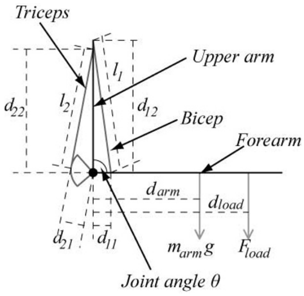

Fig. 1. Two muscle arm model, showing the flexor biceps brachii and extensor triceps brachii

-ance between the centre of the elbow joint and the centre of mass of the arm plus hand. d_{load} is the distance from the elbow to the centre of the palm, the latter being where a load force can be applied. The lengths of the bicep and tricep muscles plus the length of the free tendons are defined by l_1 and l_2.

The dynamics of this model are determined by the dynamics of the muscles and the mechanical geometry of the skeletal and soft tissue components (sections 2.2, 2.3).

2.2 Modified Parallel Hill Muscle Model with Exposed Free Tendon

The characteristic of the bicep and tricep muscles are represented by a modified parallel element Hill muscle model in series with an exposed free tendon k_t (Fig.2). The contractile element (CE) represents the force source when the muscle is activated. The damping element b_m represents energy loss within the muscle from thermal effects and mechanical inefficiency at the actin/myosin level. The parallel spring element k_m represents elasticity of the bulk muscle reflecting its ability to return to its natural length. The length x represents the length of the bulk muscle, and x_t represents the length of exposed free

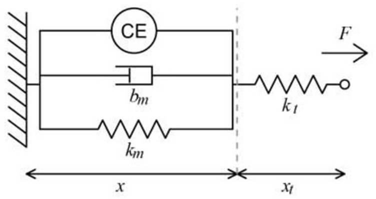

Fig. 2. Modified parallel Hill muscle model incorporating a free tendon of spring constant k_t, and length x_t. x resresents the length of the bulk of the muscle, which has a contractile element CE, damper b_m and spring k_m in parallel.

tendon. The lengths of the free tendons at both ends of a muscle are summed together and modelled as one serial spring.

Equivalent free tendon spring constants have been reported to lie in the range 60-170kN/m (Maganaris and Paul, 1999) which is much greater than the spring constants of inactive muscles. Therefore the extensions of the free tendons are considered negligible and the tendons to have fixed lengths. The length of the bulk muscle is a function of elbow angle. The result of this assumption is that when the contractile element CE is not active, the dynamics of the muscle are completely determined by the spring and damping elements. This scenario is used experimentally to allow the parameter values for the passive elements to be determined.

2.3 System Equations

The system equations (1-9) describe the elbow joint dynamics when the arm is in the same orientation as shown in Fig.1. The contractile element in the muscle model (Fig. 2) is assumed to be a pure force generator and therefore plays no part in the dynamics of the model. The upper arm is fixed in a vertical position and with the muscle not activated, the forearm and hand are allow to swing, pivoted around the elbow. The wrist is fully extended at all times.

$$\dot{\theta} = \frac{d\theta}{dt} \tag{1}$$

$$\ddot{\theta} = \frac{d\dot{\theta}}{dt} = \Big(\tau_{lim1} + \tau_{lim2} + F_1\frac{d_{11}d_{12}sin\theta}{x_1} - F_2 d_{21} + m_{arm}d_{arm}g sin\theta + m_{load}d_{load}g sin\theta - b_{arm}\dot{\theta}\Big)/J \tag{2}$$

where the angular acceleration $\ddot{\theta}$ is a sum of torques and moments. d_{11}, d_{12}, d_{21}, d_{22}, d_{arm}, d_{load} and θ are defined in Fig.1. A damping factor b_{arm} represents the resistance to movement caused by soft tissues around the elbow joint. τ_{lim1} and τ_{lim2} are the torques at the joint limits and are described in (8) and (9). J is the moment of inertia of the forearm together with any extra weight held in the palm.

The biceps force F_1 and triceps force F_2 are given by:

$$F_i = F_{CEi} + b_{mi}\dot{x}_i + k_{mi}(x_i - x_{i\_0})\,, i = 1,2 \tag{3}$$

where x_{1_0} and x_{2_0} are the natural length of the bicep and tricep muscles, excluding the length of the free tendons. As described in sections 2.2 the free tendons are assumed to have fixed lengths, but when the geometry of the model gives lengths shorter than their fixed lengths, they become slack. This means the free tendons can only transfer contractile force and therefore if $F_i < 0\,, F_i = 0$ in (3).

From Fig.1, the bicep muscle length x_1 and velocity $\dot{x}_1$ and tricep muscle length x_2 and velocity $\dot{x}_2$ are given by:

$$x_1 = \sqrt{{d_{11}}^2 + {d_{12}}^2 - 2d_{11}d_{12}cos\theta} - x_{1t} \tag{4}$$

$$\dot{x}_1 = \frac{dx_1}{dt} = \left({d_{11}}^2 + {d_{12}}^2 - 2d_{11}d_{12}cos\theta\right)^{-0.5} \cdot d_{11}d_{12}(sin\theta)\dot{\theta} \tag{5}$$

$$x_2 = \sqrt{{d_{22}}^2 - {d_{21}}^2} + d_{21}(\pi - \theta) - x_{2t} \tag{6}$$

$$\dot{x}_2 = \frac{dx_2}{dt} = -d_{21}\dot{\theta} \tag{7}$$

where x_{1t} is the bicep free tendon length and x_{2t} is the tricep free tendon length.

Additional torques resulting from soft tissue compression and extension are present near the maximum angle of flexion and extension respectively, τ_{lim1} represents additional torque at maximum extension and τ_{lim2} represents additional torque at maximum flexion.

$$\tau_{lim1} = \begin{cases} -k_{lim}(\theta - \theta_{lim1}) - b_{lim}\dot{\theta} & , \quad \theta > \theta_{lim1}, \dot{\theta} > 0 \\ -k_{lim}(\theta - \theta_{lim1}) & , \quad \theta > \theta_{lim1}, \dot{\theta} < 0 \\ 0 & , \quad \theta < \theta_{lim1} \end{cases} \tag{8}$$

$$\tau_{lim2} = \begin{cases} -k_{lim}(\theta - \theta_{lim2}) - b_{lim}\dot{\theta} & , \quad \theta < \theta_{lim2}, \dot{\theta} < 0 \\ -k_{lim}(\theta - \theta_{lim2}) & , \quad \theta < \theta_{lim1}, \dot{\theta} > 0 \\ 0 & , \quad \theta > \theta_{lim2} \end{cases} \tag{9}$$

where k_{lim} and b_{lim} represent the effective rotational spring and damping constants of the soft tissue.

Equation (2) analyses extension at the elbow joint. To analyse flexion, the upper arm needs to be in a horizontal plane with the elbow facing upwards. $\ddot{\theta}$ is now given by (10) to reflect the difference of the direction of gravity with reference to the elbow angle.

$$\ddot{\theta} = \frac{d\dot{\theta}}{dt} = \Big(\tau_{lim1} + \tau_{lim2} + F_1\frac{d_{11}d_{12}sin\theta}{x_1} - F_2 d_{21} + m_{arm}d_{arm}g cos\theta + m_{load}d_{load}g cos\theta - b_{arm}\dot{\theta}\Big)/J \tag{10}$$

3. EXPERIMENT PROTOCOL

Four healthy subjects participated in this study, none of the subjects had any known bone, muscle or nerve disease.

To parameterise the system equations to match measured data, the length and mass parameters can be directly measured or calculated. The method of measurement is described in 3.1. The arm model (see Fig.1) and system equations in section 2.3 describe a model containing an antagonist pair of muscles allowing flexion and extension of the forearm. Therefore two experimental procedures observing extension (experiment 1) and flexion (experim-