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Bond graph model of extensor mechanism of finger based on hook–string mechanism

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ABSTRACT

Biomechanical modeling of a finger is a challenging task especially due to excursion and gliding of tendons along bone geometry, the presence of articular cartilage between mating phalanges, nonlinear viscoelastic properties, load specific change in properties of tendons and complexity of deformable tendinous network (Winslow's rhombus) of the extensor mechanism. In this work, a bond graph model of the extensor mechanism of a finger is developed. Tendons are considered as deformable strings and assumed to pass through hooks fixed at predetermined points on rigid phalanges. This enables them to remain clinging to the phalanx surface while sliding on it, and retain network topology during the movement of phalanges. Word bond graph objects (WBGOs) are developed for dynamics of phalanges, hook–string interaction, normal reaction and frictional forces, and coupling of phalanges in rotation as well as translation, etc. Friction losses and extension of tendons due to applied load are accounted for. Study of motion and tension in tendons, joint variables, location of hooks and characteristics of individual tendons can be conveniently carried out based on the bond graph model. This has been effectively demonstrated through computer simulations.

1. Introduction

Modeling of musculoskeletal biomechanical systems in general and human hand in particular poses a challenging task due to its peculiarity. Tendons exhibit nonlinear time dependent viscoelastic properties. Joints are not rigidly constrained due to the presence of soft and extremely low friction articular cartilage. To add more complexity, cartilage material exhibits nonlinear viscoelastic properties [1–3]. In the musculoskeletal system, tendons are responsible for transmitting large muscle forces to bones causing them to move. Tendons are living tissues and respond to mechanical forces by changing their metabolism, structural and mechanical properties [4]. The neuro-musculoskeletal complexity of the human hand is different from other limbs [5]. Finger biomechanics become more intricate due to redundancy in muscle actuation of joints and effect of each muscle/tendon on more than one joint [6]. The development of a model, capturing mechanics of soft tendon sliding over rigid phalanx geometry, even as it moves, and transmission of tension, is challenging and of interest.

Versatility and flexibility of bond graph [7–10] make it a potential problem solving tool for this elaborate biomechanical system. Bond graph is a domain-independent graphical description of dynamic behavior of physical systems (e.g. electrical, mechanical, hydraulic, acoustic, thermodynamic, material, and so on). It is based on transactions of power and depicts causality of physical systems in a simple and elegant manner. Derivation of system equations and coding for simulation can be done directly and algorithmically

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Nomenclature

C_i	center of mass of bone i
$\left[{}^{0}_{C_i}I_i\right]$	inertia tensor of bone i with respect to its center of mass, expressed in inertial frame $\{\mathbf{0}\}$; $\in \mathbb{R}^{3\times 3}$
K_i	stiffness element attached to bond i; $\in \mathbb{R}^1$
$[K_j]$	stiffness tensor attached to multibond j; $\in \mathbb{R}^{3\times 3}$
${}^{0}\overline{p}_i$	translational momentum of bone i observed and expressed in the inertial frame $\{\mathbf{0}\}$; $\in \mathbb{R}^3$
${}^{0}_{C_i}\overline{p}_i$	angular momentum vector of bone i with respect to its center of mass and expressed in inertial frame $\{\mathbf{0}\}$; $\in \mathbb{R}^3$
R_i	damping element attached to bond i; $\in \mathbb{R}^1$
${}^{0}_{i}R$	rotation matrix describing orientation of frame $\{\mathbf{i}\}$ with respect to inertial frame $\{\mathbf{0}\}$; $\in \mathbb{R}^{3\times 3}$
${}^{0}_{i}\dot{R}$	time derivative of ${}^{0}_{i}R$; $\in \mathbb{R}^{3\times 3}$
${}^{0}_{0}\dot{\overline{r}}_{C_i}$	velocity of center of mass of the bone i observed and expressed in inertial frame $\{\mathbf{0}\}$; $\in \mathbb{R}^3$
$\dot{S}_{P_i}$	speed of string end at P_i; $\in \mathbb{R}^1$
$\left[{}^{0}_{C_i}\overline{r}_{O_{ij}}\times\right]$	skew symmetric cross product matrix obtained from vector ${}^{0}_{Ci}\overline{r}_{O_{ij}}$; $\in \mathbb{R}^{3\times 3}$
$[U]$	unit matrix; $\in \mathbb{R}^{3\times 3}$
${}^{0}_{0}\overline{\omega}_i$	angular velocity vector of frame $\{\mathbf{i}\}$, observed and expressed in the inertial frame $\{\mathbf{0}\}$; $\in \mathbb{R}^3$
EIP	Extensor Indices Proprius
EDC	Extensor Digitorum Communis
PI	Palmer Interosseous
LUM	First Lumbrical

from the bond graph. Bond graph modeling captures intricacies of the biomechanical system of the finger very systematically and translates them into a numerically solvable mathematical model. The model is then translated into computer code for numerical integration. The simulation is available in the form of time trajectories of states. All variables that depend on these states can be numerically determined. Bond graph is extensively used to model multibody systems, consisting of rigid and elastic bodies joined by translational or rotational joint characteristics. Simple kinematic relations are used to construct the bond graph structure and dynamics is appended on it to complete the bond graph model [11].

In the next section, the uniqueness of the extensor mechanism of the human finger is discussed along with the work of various researchers. Tendinous network of the extensor mechanism is explained. Winslow's topology of extensor mechanism is elaborated along with terminology associated with it. The dynamics involved in rotational and translational sub-systems and subsequent development of Word Bond Graph Objects (WBGO) and normal reaction between floating points on tendons and curved bone surface is discussed in Section 3. Concept and development of mechanics of the hook string sub-system is elaborated step by step. In Section 4, the bond graph model is converted into computer code and simulated. Results showing the dynamic behavior of the model, with the help of position trajectories of centers of mass, hooks, floating points, etc., tensions in tendons, are explained.

2. Extensor mechanism of finger

The anatomy of the hand is efficiently organized to carry out a variety of complex tasks. These tasks require a combination of intricate movements and finely controlled generation of force. The shape of the bony anatomy in conjunction with the arrangement of soft tissues contributes to the complex kinematics of the hand [12]. Function of tendons is to transmit forces from muscles to the phalanges in order to actuate joints. The tendon lubrication system reduces friction during tendon excursion. In many cases tendons cross more than one joint and impart rotation to these joints. Tendons graze along the bone while transferring force to the bone and maintain proximity to the bone while providing rotation to the corresponding joint. Geometric changes take place in the tendon topology of the extensor mechanism in different postures of the finger. Changes in length of its different parts may be small, but their spatial orientation varies significantly [13]. Proper excursion and gliding of the tendon determine the efficiency of the tendon in transmitting muscle forces to the skeletal system [14].

Available literature deals with the kinematics and dynamics of the human hand or finger systems [15–18]. Lagrangian formulations have been the basis of most of these models. Modeling complexities such as joint and tendon friction, and interaction of soft muscles with rigid skeletal dynamics are difficult using this approach, and require simplifying assumptions, and have not been considered in these models.

The extensor mechanism of fingers, contain complex tendinous networks and were not previously amenable to biomechanical simulation. Valero-Cuevas and Lipson [19] proposed a computational environment to describe and simulate 3D biomechanical systems. Two different topologies of the extensor mechanism were simulated and it was observed that all other things being equal, moderate changes in the topology of the extensor mechanism greatly affect the distribution of load through its individual elements, and will affect the biomechanical predictions of finger motion and force.

Experimental studies of finger forces for various patterns of muscle excitation have been reported in [20–22].