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Research paper

Bond graph modeling of a 3-joint string-tube actuated finger prosthesis

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ABSTRACT

In prosthetic systems, the mechanism, sensing and actuation systems, and controls are some of the important areas which require modeling and analysis. Causal representation based on power transactions provides better understanding of interactions between these subsystems. A unified approach is therefore required to deal with the dynamics of such systems. Bond graph offers such a unified approach to the dynamics of such biomechanical systems. The concept of Word Bond Graph Objects (WBGOs) provides several advantages in modeling such large systems, including: compact representation; facilitation of understanding of energetic and causal interactions between component subsystems; algorithmic, quick and easy object oriented programming for numerical simulations. The approach had been applied earlier to develop models for a class of hand prosthesis. This work is an elaborate extension to a redundant under-actuated three-joint string-tube based finger prosthesis for a partially impaired hand. It systematically explains the dynamics of behavior of the mechanism, interactions at translational and revolute couplings between rigid phalanges, and, string-tube based joint actuation principles involved in this class of prosthesis through simulations of the bond graph models.

1. Introduction

The concept of Word Bond Graph Object modules (WBGOs) was introduced earlier by the authors for modeling the dynamics of large physical systems. This compact graphic representation, which is based on the bond graph technique, invented and disseminated by Henry Paynter in 1959 [22,25] was applied to the important area of modeling the skeletal mechanism of a human hand with a view to the design and development of hand prosthesis. Modeling using the WBGOs approach is especially suitable for biomechanical systems and prosthetic systems, which are usually large with interconnections and interactions in more than one energy domain.

For an exhaustive survey of literature related to the human hand from various perspectives, the reader is referred to the review paper by Bicchi [5]. A brief survey of relevant literature is presented below to provide a background leading to the present work. The relevant literature is grouped into prosthetic mechanisms for the human hand with finger and their modeling, mathematical modeling of musculoskeletal actuation, bond graph modeling applied to musculoskeletal systems for the hand and its prosthesis.

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1.1. Prosthetic mechanisms for the human hand with finger and their modeling

Prosthetic mechanisms for the human hand have been inspired by its anatomy which makes it more realistic for rehabilitation purposes [30]. The mathematical modeling of such biomechanical systems has always been a challenge for researchers. These mathematical models are supposed to provide understanding of the nature of forces on phalanges, tendons, and torques at joints, for actuating the fingers while performing tasks. Cole et al. [10] developed a tendon driven prosthetic device, wearable as a glove, for the partial hand amputee. The device was a passive prosthetic type drawing energy for actuation from the human body itself. Becker and Thakor [3] studied the tendon actuation using SMA wire based actuators, of a two joint finger and compared results with normal hand motion. They were able to study the range of motion data for maximum tendon displacements and angular displacements at joints. The role of extensor, flexor and intrinsic tendons was also studied by them.

Prehensile tasks performed by the hand were analyzed and studied by Thea Iberall and others [1] and the principle of *Opposition Space* was proposed. Most of the common prehensile tasks performed by the hand were categorized into three categories under the principle of *Opposition Space*. These were: the *pad opposition*, the *palm opposition* and the *side opposition*. The principle was also proposed as an abstract structuring concept for the analysis of skilled hand movements [16,17].

Robert Vinet et al. [38] designed and developed a multifunctional hand prosthesis. Kinematics of biomechanical model of the thumb was explored by Valero-Cuevas et al. [31] for understanding clinical problems.

Suitable mechanisms were needed to implement the concepts of *opposition space* [15] as applied to prosthesis. These were proposed and demonstrated by Vaz and Hirai [33]. The *string-tube* mechanism in *like* and *unlike* configurations was proposed and demonstrated [36]. The idea of *opposition space* could be conveniently applied using the *unlike* configuration. The movement of passive prosthetic finger joints was made possible by active good finger joints. The string-tube mechanism in *like* and *unlike* configurations has the potential to go beyond the concept of *opposition space*.

1.2. Computational and experimental works on anthropomorphic robotic fingers

Mechatronic design of anthropomorphic robot finger was developed and experimentally tested at a preliminary level by Biagiotti et al. [4]. Experimental setups for anatomical robotic hand, have been developed as anatomically correct testbed (ACT), to understand the kinematic behaviour of finger joints and phalanges [40,39,20], including the thumb [7]. A three phalanx underactuated tendon based finger mechanism was proposed and analyzed by Birglen and Gosselin [6]. Lan and Yang [23] proposed a computational design method for a SMA wire actuated compliant finger. Biomechanical models for musculoskeletal actuation of human fingers have been proposed by researchers [32,13,37].

1.3. Mathematical modeling and control of robotic hand

The literature available on this topic is extremely vast and it is not the main focus of the present work. Hence, a brief review of the modeling and control of robotic hand systems based on tendon actuation is carried out here.

Salisbury and Craig [28] addressed the kinematic and force control issues of dexterous robotic articulated hands for achieving different types of manipulation tasks. They introduced considerations of mobility, force application accuracy, singularities, noise propagation, parameter optimization and control system structure. Dynamic simulation of 3-joint tendon driven manipulators was carried out by Lee and Tsai [24]. A control strategy for tendon driven actuation systems for manipulators was proposed and implemented by Jacobsen et al. [18] for a single joint system. Cole et al. presented detailed kinematics and control of multifingered hands with rolling contact [26,9]. The formulation was based on Lagrange's energy based method. Cutkosky presented an analytical model of robotic hand grasping and manipulation for industrial applications [12]. The dexterous manipulation problem with a robotic hand has been formulated by researchers [26,27]. It was shown by Balasubramanian et al. [2] that the response of an underactuated hand to external disturbance contact forces are a function of coupling mechanism, actuation mode and contact constraints.

1.4. Bond graph modeling applied to musculoskeletal systems for the hand and its prosthesis

Since its invention, the method of bond graph has evolved into an elegant and powerful technique for the modeling of physical system dynamics. Biomechanical systems and prosthetic systems in particular are useful applications well suited for this technique. The method of bond graph offers a unified framework for modeling the mechanism, actuation and control systems due to its capability of handling multi-energy domains [22,25]. Multibond graphs help in creating compact models of large systems [25,19]. Word bond graph [22] and capsules are some of the related concepts already known to exist in bond graph literature. Word Bond Graph Object (WBGO) modules are developments of these representations into a form which is convenient for object oriented programming, required for numerical simulation. WBGOs can be used to represent similar subsystems in an overall system. They facilitate assembly to model large and complex systems, in a graphical and intuitive manner. Thus, they help in further compacting the representation and at the same time provide a clear perspective of the overall system, its components and their interactions in terms of power and causality. Programming code for simulation, based on WBGOs, can be developed systematically and rapidly in an algorithmic manner.