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Description of the human hand grasp using graph theory

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ABSTRACT

This paper presents a method to describe and analyze the human hand grasp postures so as to indicate which fingers should act during grasping and the required movements of those fingers. The method first describes the human hand with human hand tree graph and incidence matrix, and then the relationship between the human hand and the grasped object is described by grasp contact graph and basic cycle matrix that can be divided into an identity matrix and a B_{f12} matrix. The nonzero columns of the B_{f12} matrix can be described by a graph called VF-tree, which can indicate which fingers are active while grasping and the required degree of freedom of each finger. The method is validated by describing and analyzing the six basic grasp postures of the human hand.

1. Introduction

The human hand is an important tool that helps the human being to perform various operations in daily life. By studying structure, behavior and grasp functions of the human hand, people can know more about it so as to design a bionic hand for rehabilitation or other applications.

To describe and analyze the human hand, hand models are usually built according to musculoskeletal structure, kinematics [1,2] and grasp analysis. Yasumuro et al. [3] modeled the skeleton structure of human hand with a hierarchical structure represented by a tree, where the root is the wrist. Kuch and Huang [4] provided a hand model with 23 DOFs (degree of freedom) based on the anatomy structure of human hand. The thumb has 5 DOFs, each of other four fingers has 4 DOFs, and the last 2 DOFs are located at the base of ring finger and little finger metacarpals. The model can be used in numerous HCI (human computer interaction) scenarios. Based on the generalized function set theory, Yang et al. [5] presented the characteristic tree of the human hand for kinematic characteristics analysis, and classified states of human hand into six categories from the view point of topology. Using principal components analysis, simplified human hand models with different DOFs were presented for different required tasks [6]. Park and Cheong [7] presented a method for analyzing and synthesizing human's grasp motion and the corresponding collective behaviors. Human hand structure with natural constraints was defined. In the human hand structure, where the thumb has 3 DOFs and each of other four fingers has 4 DOFs.

The classification of human hand grasp has been studied in anthropology, rehabilitation and medical science. In order to capture human hand versatility for designing prosthetic hands, Schlesinger developed a classic taxonomy of human hand grasp consisting of cylindrical grasp, precision grasp, hook prehension, tip grasp, spherical grasp, and lateral hip [8]. Napier [9] presented a prehensile classification based on function and anatomy structure of human hand, and grasp tasks are divided into power grasp and precision grasp. Based on the concept of virtual finger (VF) [10], Iberall et al. [11] proposed a classification of human hand grasp including pad opposition, palm opposition and side opposition. There are also some other classification studies about gravity-dependent grasps [12] and dynamic hand movements [13].

For human hand grasp description, there have been some researches discussing force or contact relation of the human hand and the grasped object, grasp force imposed on object, virtual fingers and opposition space, etc. Arbib et al. presented the concept of virtual finger, which is an abstract representation with a function unit for a collection of individual fingers and hand surfaces applying an opposition force. A single finger or a palm can be a VF, and several fingers grouped together to apply force or torque opposing other VFs or task torques can also be a VF [10,14]. Iberall et al. proposed the term opposition to describe three basic directions where the human hand can apply forces, which includes pad opposition that occurs between hand surfaces along a direction generally parallel to the palm, palm opposition that occurs between hand surfaces along

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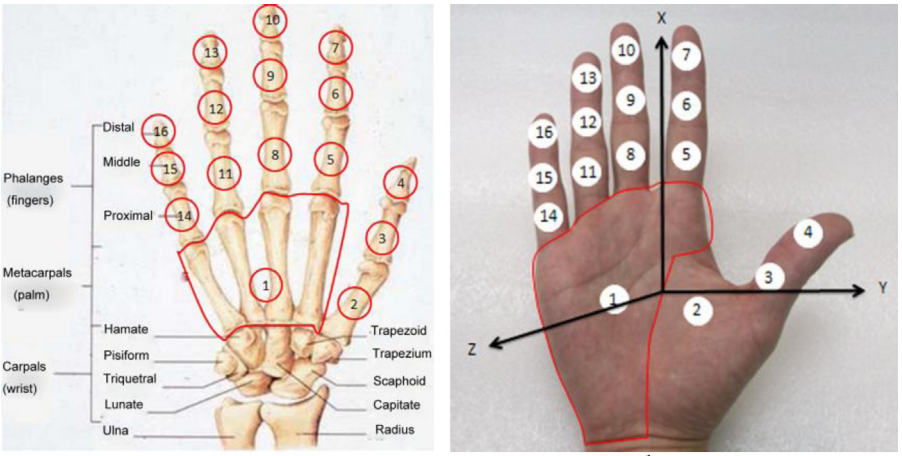

Fig. 1. (a) Contact areas on human hand skeleton and (b) contact areas on a human hand.

a direction generally perpendicular to the palm, and side opposition that occurs between hand surfaces along a direction generally transverse to the palm. The opposition space can be described by both physical terms such as amount and orientation of force vectors and abstract terms such as types and numbers of oppositions, virtual-to-real finger mappings, VF lengths [14]. Kang and Ikeuchi [15] introduced a concept of contact web that is composed of a pattern of effective contact points between the human hand and the grasped object. Based on the contact web, a grasp taxonomy and grasp recognition approach were proposed [16]. Miller et al. [17] developed a system called "GraspIt!" to describe and analyze human hand grasp based on computer modeling and simulation. Kim et al. [18] discussed two methods that could predict when and how fingers would slip upon a grasped object and described the hand grasp by measuring grasp and friction forces. Fu and Santello [19] presented a framework for a complete kinematic description of grasping including hand and objects, and introduced how to estimate contact sites on both the hand and object. The framework was verified by two grasp experiments, but it is sensitive to missing markers.

In addition, human hand grasp planning [20–22] and human hand contact force [23–25] have also been investigated and related with human hand grasp posture.

A human hand grasp task involves three phases: pre-grasp phase, static grasp phase and manipulation phase [15]. This paper focuses on the description and mathematical analysis of the contact relationship of the human hand and the grasped object in static grasp phase.

2. Methods

2.1. Human hand tree graph

Human hand tree graph is used to describe the human hand based on anatomy structure and the distribution of DOFs via graph theory. A human hand skeleton (Fig. 1a) [26] consists of 8 carpal bones, 5 metacarpal bones and 14 phalanges, and each finger except the thumb has proximal, middle and distal phalanges, whereas the thumb has only proximal and distal phalanges [3]. How to plot contact areas of human hand is crucial for building human hand tree graph. Based on the concept of intradigital contact points and interdigital contact points, the human hand can be plotted out of 15 contact areas by regarding the palm and the metacarpals of the thumb as one contact area [15]. However, the metacarpal of the thumb is different from the palm because it has DOFs, so it ought

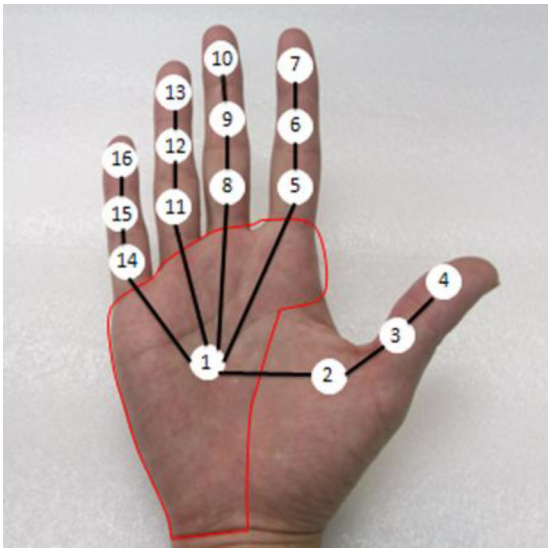

Fig. 2. Human hand tree graph.

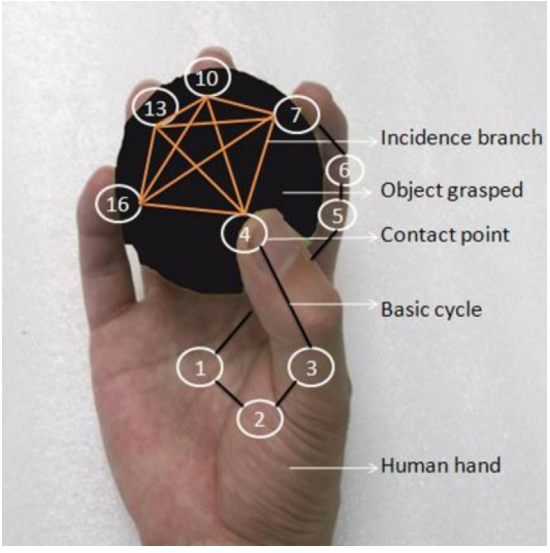

Fig. 3. Description of the human hand grasp.