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Exploring the existence of better hands for manipulation than the human hand based on hand proportions

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ABSTRACT

Human exhibits the most dexterous manual manipulation among the anthropoids. The sophisticated dexterity of human hand has been linked to its distinctive morphology compared to the nonhuman anthropoids. The human hand is derived from the ancestral hands after longtime evolution. However, there are more possible morphologies that the hands could take during the evolutionary process. It remains unknown whether better hands for manipulation than the human hand exist among these possible hands. To answer the question, the relationship between the manipulative capability and hand morphology need to be investigated in the region of more possible hands. Here we employ a kinematic model to quantitatively assess the manipulative ability of the possible hands from the aspect of hand proportions. The segment length proportions of each possible hand are reconstructed by the major evolutionary patterns of the anthropoid hands. Our results reveal that too long and too short thumbs relative to fingers both hamper the manual dexterity, though the long thumb of human hand is traditionally thought to be beneficial to manipulation. The results promote the understanding of the link between hand morphology and function. Furthermore, we find out the optimal hand for dexterous manipulation within the region reconstructed by the major evolutionary patterns of the anthropoid hands. The optimal hand is more dexterous than the human hand. Compared to the optimal hand, the human hand has shorter metacarpals relative to phalanges, which is thought to be advantageous to the prehensility. It suggests that the human hand is not an organ exclusive for the dexterous manipulation, but a trade-off between multiple functions.

1. Introduction

Object manipulation by hand is known as one of the major characteristics of the anthropoids (Cartmill, 1974; Matsuzawa, 2008). This characteristic is a precursor of tool-using and tool-making, which are important for the survival and reproduction of the anthropoids (Call, 2013; Parker, 1974b). The anthropoids exhibit various manipulative abilities among different species (Parker, 1974a; Torigoe, 1985). Humans hold the best manual manipulative skills among the anthropoids (Napier, 1960; Napier et al., 1993). Compared to the nonhuman anthropoids, humans can perform more complex manipulative tasks and possess larger repertoire of manipulations (Parrish and Brosnan, 2012). Besides, the human hand exhibits tremendous dexterity and serves us extremely well in a mass of ways during the daily life (Jones and Lederman, 2006). It is natural for researchers to make great efforts to study the factors contributing to the dexterous manipulation (Bianchi and Moscatelli, 2016; Marzke, 1997) and attempt to reproduce the superior ability of the human hand in the design of robotic hands (Bicchi, 2000; Borràs and Dollar, 2015; Xiong et al., 2016). However, there are more possible morphologies that the hands could take during the evolutionary process. Among the possible hand morphologies, there might exist more suitable morphologies for manipulation than the human hand morphology. To explore the better hands for manipulation than the human hand, we investigate how the morphology of hand proportions impacts the manipulative ability in larger region than the anthropoid hands.

The functional relationship between hand proportions and manipulative capability has been built through both qualitative and quantitative studies. The manipulative ability is traditionally inferred through the qualitative comparisons of morphological features and behavioral observations among different species (Boyer et al., 2013; Marzke, 1997; Susman, 1994). For example, the long thumb relative to fingers is considered advantageous for manipulation (Alba et al., 2003; Marzke, 2013). Except for the qualitative inferences, the quantitative assessments about the manipulation of anthropoids are also performed through the simulation and modelling (Feix et al., 2015; Liu et al., 2016; Niewoehner et al., 2003).

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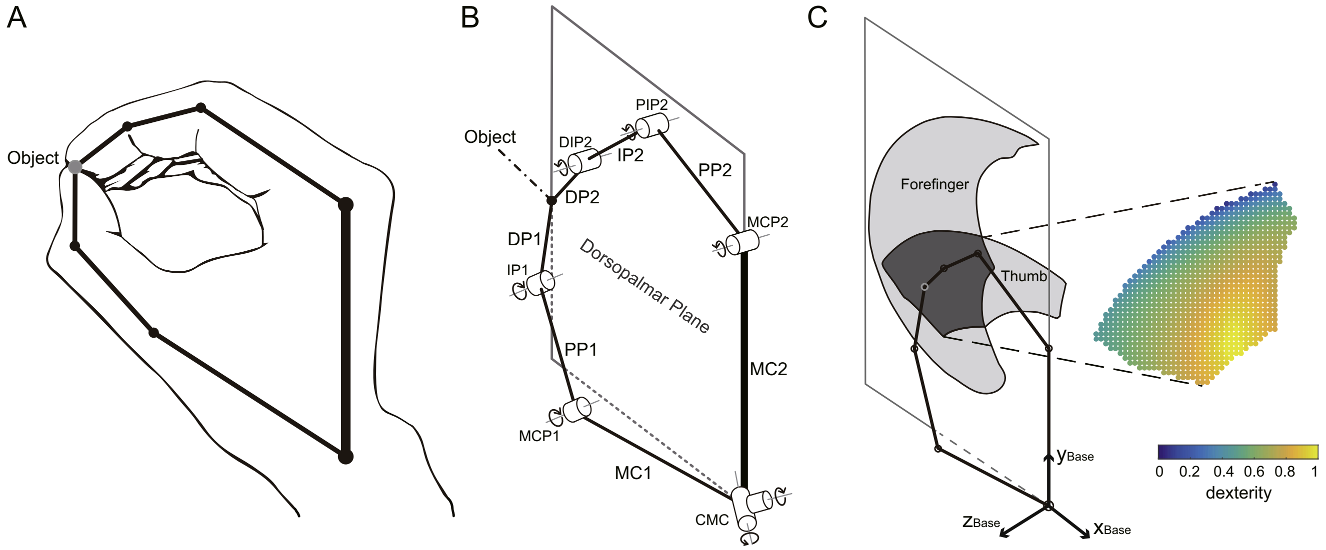

Fig. 1. Kinematic model of the thumb-forefinger tip-to-tip manipulation. (A) Drawing of the in-hand manipulation between the tips of the thumb and forefinger. Here we take the human hand as an example. (B) Simplified model of the skeletons and joints for the in-hand manipulation. The kinematic model has three thumb links (first metacarpal (MC1), proximal phalanx (PP1) and distal phalanx (DP1)) and four forefinger links (MC2, PP2, second intermediate phalanx (IP2) and DP2) with a total of 7 degrees of freedom. The MC2 is fixed as the ground link. All the links are connected through five hinge joints and one universal joints. Abbreviation of the joints: CMC, carpometacarpal phalangeal joint of thumb; MCP1, metacarpophalangeal joint of thumb; IP1, interphalangeal joint of thumb; MCP2, metacarpophalangeal joint of forefinger; PIP2, proximal interphalangeal joint of forefinger; and DIP2, distal interphalangeal joint of forefinger. (C) The dexterity within the workspace of the in-hand manipulation. The overlapping region between the reachable areas of the thumb and forefinger denotes the workspace where a tip-pinch can be made. Within the workspace, the magnitude of dexterity in each local point is denoted by colors as shown in the legend. The larger workspace and higher dexterity within the workspace manifest better manipulative potential. The figures are drawn with the average hand proportions of human. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

By means of the quantitative analyses, the effect of hand proportions on manipulation can be more precisely assessed. These studies reveal the link between hand morphology and hand function from many different viewpoints. However, they are only performed within the scope of extant and fossil anthropoids.

The morphology and function of the anthropoid hands are the products of longtime evolution. Over the course of human evolution, the hand was free from the constraint of locomotion and evolved primarily for manipulation (Jones and Lederman, 2006; Kemble, 1987; Marzke, 1992). Although the nonhuman anthropoids need to evolve under extra constraints of locomotion except for manipulation (Gatesy and Pollard, 2011; Pontzer, 2012; Preuschoft et al., 1993), their hands can also perform certain precision grips and dexterous manipulations (de A. Moura and Lee, 2004; Haslam et al., 2009; Neufuss et al., 2017). Generally speaking, the anthropoids as a whole possess enhanced manual manipulation compared to other mammals. The analogous phenotypes and behaviors observed among different species are the reflex of a common ancestor or similar environmental challenges (Wilson, 2000). In the matter of the anthropoid hands, the variances of manual segment proportions embody their evolutionary patterns. The major evolutionary patterns presumably reflect the morphological features contributing to manipulative skills, which are the common functional requirements of the anthropoids. Therefore, we explore better hands for manipulation than human hand among more possible hands, which are reconstructed by the major evolutionary patterns of the anthropoid hands.

As the possible hands are beyond the scope of extant anthropoid hands, their manipulations cannot be estimated through observations. The kinematic model is required to simulate the digit movements of the possible hands. The anthropoid hands can perform many different manipulative tasks. Among the wide range of the manipulation modes, the thumb-forefinger tip-to-tip manipulation is not only important to precise manual skills (Bullock et al., 2013; Neumann, 2013), but also critical in the evolutionary history for tool-related behaviors (Marzke and Shackley, 1986). Thus, we simulate this in-hand manipulation in our kinematic model (Fig. 1) to assess the manipulative potentials from hand proportions. Here, the concept of manipulative potential is derived from the former study (Liu et al., 2016), referring to the inherent potential of manipulation based on the hand proportions itself.

In this study, we explored the manipulative potentials of more possible hands to seek the better hand proportions for manipulation than the human hand. First, the possible hand proportions were reconstructed based on the major evolutionary patterns of the anthropoid hand proportions. The major evolutionary patterns were extracted from the manual segment lengths of 137 extant anthropoid samples by using a principal component analysis (PCA). Second, we referred to the previous study (Liu et al., 2016) and built a kinematic model to assess the manipulative potentials of the possible hands. Third, we studied the variation of manipulative potentials and segment proportions among the possible hands. Based on the characteristics of manipulative potential variation, we tried to find an optimal hand with the highest manipulative potential. It should be noted that the exploration of the optimal hand depends on the measurement for manipulative potential. In this study, the manipulative potential is measured by a global manipulative index (GMI), which is based on the size of workspace and the dexterity within the workspace. Besides, the search region of the optimal hand is within the major evolutionary patterns of the anthropoid hands. Fourth, we compared the segment proportions and manipulative potentials between the optimal hand and extant anthropoid hands, especially the human hand. By means of these works, we hope that this study can not only advance the cognition of the link between hand morphology and function, but also contribute to the understanding of the structure and functions of the human hand.

2. Material and methods

The kinematic model and the measurement of manipulability used in this paper have been described in the previous study