Kinematic Analysis of the Human Thumb with Foldable Palm to Understand its Role in Grasp Affordances

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***Abstract*— Humans demonstrate remarkable capabilities to use a variety of grasp strategies for a given object depending on the context of the task - often referred to as grasp affordances in dexterous hands. The interplay among the nervous system, the morphology of the human hand, and the properties of the object to demonstrate these advanced grasp affordance skills are not well understood yet. A key hypothesis addressed in this paper is that the kinematics of the human thumb together with the foldable palm offer a wide variety of choices for the nervous system to plan grasp affordances. This paper provides a new kinematic model to abstract the complex musculo-skeletal arrangement of the human thumb, so that its key morphological contributions to wider grasp affordances can be better understood. It also allows to simplify the grasp affordance control strategies. The model was validated using human grasp data base consisting of demonstrations for sixteen grasp types across five human subjects.**

I. INTRODUCTION

The complex bones, muscles and tendon arrangement in the human hand gives its dexterity. Does hand's capability in grasping objects according to its intended task, yield from its morphological configuration or from the cortical mechanism or from both? The concept of *affordance* put forward in [1] explains how an object affords to the user. The involvement of human cortical motor processing in object grasping has been studied in various perspectives such as in [2], [3].

Though most biomechanical features of the human hand have been understood [4], [5] and successfully replicated [6], the complex mechanisms of how the thumb works together with the foldable palm according to grasp affordances is not well understood.

A new kinematic model was developed to abstract the essential morphological features of the human thumb and to understand how the nervous system recruits synergies among joints for different grasp affordances. We attempted to understand any existing joint relationships in functional tasks that could be extended to robotic tool use in unstructured environments. Third order regression analysis show that there are set of synergies span across common grasp choices [7] and it varies among the subjects considered. This suggests that the brain dynamically controls relationships among joints depending on the grasp affordance.

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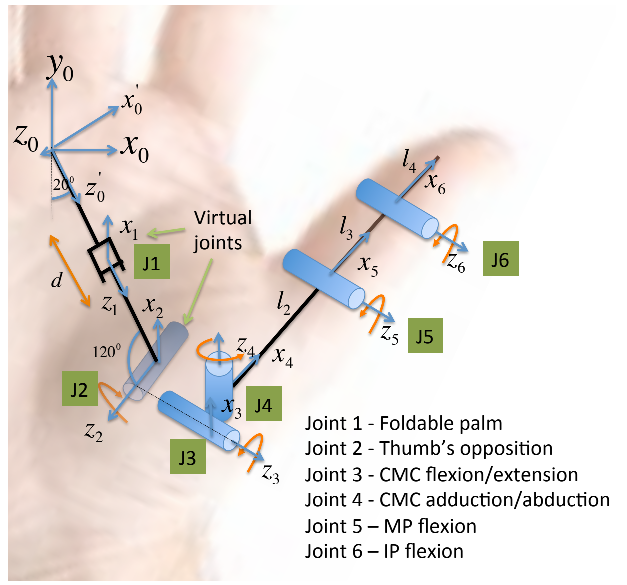

Fig. 1. Six DOF thumb kinematic model

II. KINEMATIC DESIGN

We abstracted the thumb and the palm configuration into 6 Degrees Of Freedom (DOF) using 1 prismatic (J1) and 5 revolute joints (J2-J6) as shown in Fig. 1. J1, with its translational motion, d along the palm plane, is introduced as a simplified abstraction to study the palm cupping formation with thumb's opposition movement in grasping. A revolute joint (J2) represents this opposition motion with its rotational axis aligned to the J1 translation axis by 60^0 in the same open palm plane.

Thumb's CMC joint is represented as two revolute joints with orthogonal and intersecting rotational axes for flexion-extension (J3) and adduction-abduction (J4) with their intersecting point on the palm. J5 and J6, which represent Metacarpophalangeal (MP) and Interphalangeal (IP) joints respectively cause flexion-extension. Their axes are taken to be parallel and align along the biological joint axes. J2-J6 joint angles are represented by $\theta_2 - \theta_6$. We treated thumb link lengths $(l_2 - l_4)$ as observed variables. Using standard equations [9], joint orientation and positions were calculated and the model was validated using the human thumb tip position and rotation matrix grasp data set (trial 1), for 5 subjects, 16 grasp types, and 100 samples [8].

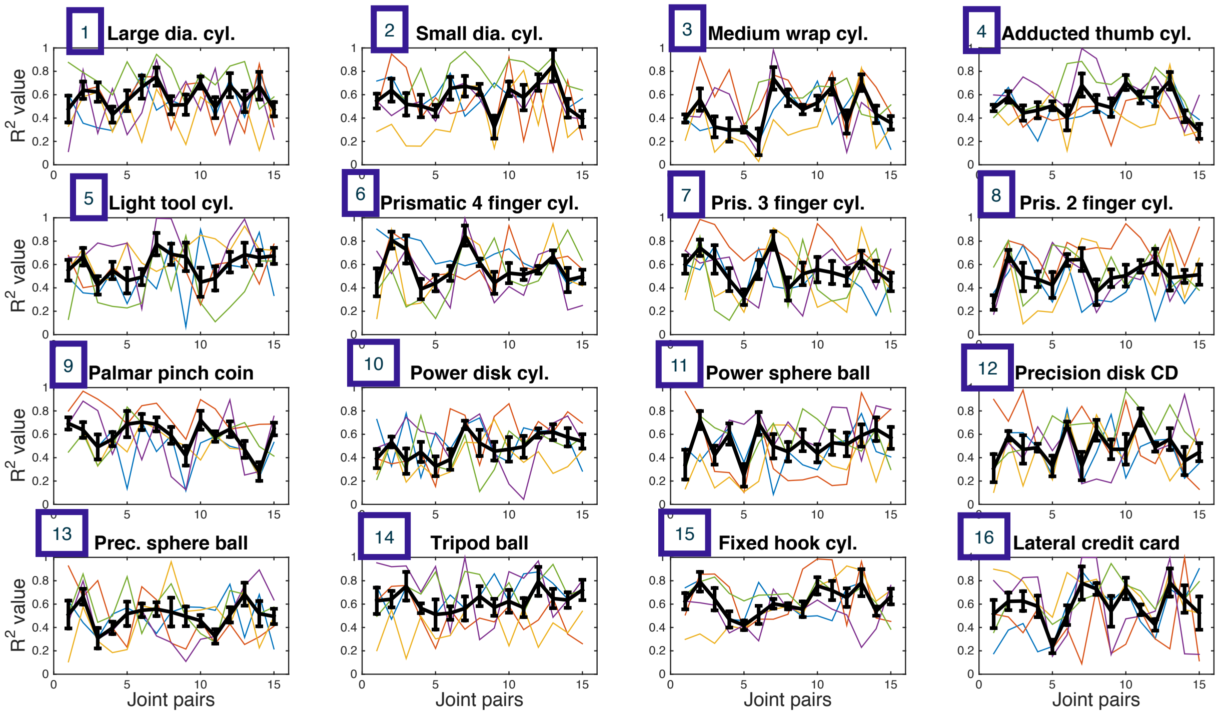

Fig. 2. Black lines denote the median R^2 values for all 5 subjects plotted against pairs of joints for the 16 grasp types [8] along with individual R^2 values, in colour lines, for comparison. The vertical error bars represent the standard error across 5 subjects. The order of 15 joint pairs numbered as (**P1:P15**) are: **P1**: (θ_2, θ_3), **P2**: (θ_2, θ_4), **P3**: (θ_2, θ_5), **P4**: (θ_2, θ_6),**P5**: (θ_2, d), **P6**: (θ_3, θ_4), **P7**: (θ_3, θ_5), **P8**: (θ_3, θ_6), **P9**: (θ_3, d), **P10**: (θ_4, θ_5), **P11**: (θ_4, θ_6), **P12**: (θ_4, d), **P13**: (θ_5, θ_6), **P14**: (θ_5, d), **P15**: (θ_6, d)

III. Results and Discussions

We looked at the R^2 values of 3rd order polynomial models between joint pairs of the kinematic model to understand the behavior of joint synergies if at all. The R^2 value represents the degree to which the model explains the variability of the two kinematic variables considered in any given pair. Therefore high R^2 values indicate that there is a distinct non-linear relationship between the pair of joints concerned. For example in Fig. 2, the most frequent synergy pair, **P13** in grasps 2, 3, 4, and 15 (in grasping a 3 cm diameter cylinder) is associated with MP and IP joint flexion-extension. Grasps 3 and 4 show another significant synergy in pair, **P7** denoting CMC and MP flexion-extension. Whereas, in grasping a 1 cm diameter cylinder (grasps 5, 6, 7, and 8), there are relatively higher R^2 values in joint pair, **P2** for thumbs opposition and adduction-abduction and **P7** for CMC and MP flexion-extension.

However, model fitting to human grasp data across 16-grasp types reveal that the palm folding is controlled independently from synergies in the thumb. Even though there is only a single noticeable synergy in joint pair, **P9** in grasp 9.

We further noticed from Fig. 2 that, synergies depend on the specific grasp type and it is not consistent among individuals. This suggests that grasp synergies are mostly controlled at a neural level than as a fixed musculo-skeletal feature.

Synergies in the thumb show statistically significantly different variability across subjects ($p < 0.05$, Mann-Whitney U-test) except 13th grasp type (precision sphere ball). This variability across subjects most likely comes from neural plasticity to learn different joint synergies to suit different grasp optimality criteria than due to variability of hand morphology. This implies that anthropomorphic robotic hands can accomplish successful grasps without having to follow a generic template of synergies. These findings provide useful design guidelines for prosthetic or wearable hand extensions that can be controlled with flexible synergies.

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