

Computational Model of Articulating Hand for Aid in Biologically-Motivated Design of Functional Hand Protheses

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1. INTRODUCTION

Designing a functional artificial hand is one of the most difficult challenges currently facing upper limb protheses designers. When designing such a device, several questions present themselves. What functions should the artificial hand be capable of performing? What degrees of freedom are required to perform the desired functions? What mechanisms are required in order to articulate the hand? What forces and torques will be required of the driving mechanisms?

Intuitively, one might begin addressing these issues by gaining a better understanding of the musculoskeletal dynamics involved in natural human hand movements. One could observe how the natural hand accomplishes the task(s) desired for the artificial hand to perform and use these observations to aid in the design process. The development of a computational model of the natural human hand would provide the means to analyze the musculoskeletal dynamics involved in performing general hand movements. Such a model could be used to observe the amount of articulation required (degrees of freedom) and the forces and torques required to articulate the hand. Based on such observations, inferences can be made concerning which degrees of freedom and mechanisms would be required, including the forces and torques the mechanisms would be required to produce/tolerate. Observations of natural hand function can then serve as a starting point and end goal of the design process, where approximation of the natural human hand is the desired goal.

The human hand has many degrees of freedom which allow it to perform thousands of functions. For a functional prosthesis designer, the choice of which functions to include is often limited by the degrees of freedom—and therefore the complexity of the articulation—involved. One example of a commonly performed hand function which requires complex articulation is grasping a ball or apple-sized spherical shaped object. The “ball grasp” movement requires movement of all of the fingers, and thumb, at all of their respective joints. Here I present observations obtained using a computational model of the natural human performing a ball grasp. Preliminary observations from dynamical analyses provide potential insight into issues which would be faced in the design of functional hand protheses capable of performing a ball grasp.

2. METHODS

The computational model used in this study was developed in OpenSim, an open source biomechanics software. The current model was based on the Stanford VA Upper Extremity (Stanford) Model [1], available online in the OpenSim neuromuscular biomechanics library. The Stanford VA Model included a nearly fully articulated right arm, complete with a fully articulated shoulder, elbow, wrist, thumb, and index finger. The model also included all of the muscles necessary for articulating all of the remaining three fingers in the hand, although the joints in these fingers were initially modeled as weld joints.

The knuckles and other two joints in each of the remaining fingers were added to the Stanford VA Model to allow articulation of all of the phalanges. The metacarpal-proximal phalangeal joints (knuckles) were

modeled as universal joints with two degrees of freedom (flexion and ab/adduction) in an analogous manner to the articulation of the index finger already included in the model. The joints between the proximal, middle, and distal phalanges of the remaining fingers were modeled as hinge joints with one degree of freedom each. Thus, all four of the fingers of the model's right hand had universal joints at the knuckles and hinge joints between phalanges (Figure 1). In addition, the thumb had four degrees of freedom, including a universal joint at the metacarpal-trapezium joint and hinge joints between the first metacarpal and proximal phalange and between the first proximal and distal phalange. The axes of rotation for the joints of the middle, ring, and little finger were determined based on observations of a single adult male subject. Wrapping surfaces were added to ensure that muscles did not pass through bones at any possible position for each of the fingers. Similar wrapping surfaces for the index finger and thumb were already included in the Stanford VA model.

The thorax, head, and shoulder bones (including the clavicle and scapula) were removed from the model. The humerus was redefined as ground and the elbow joint was locked. Supination was also locked in the model with the palm of the hand facing posteriorly. All muscles not involved in hand movement were removed, and the attachment points of those muscles involved in hand movement were redefined relative to the humerus (ground) when necessary. No muscle properties for the remaining muscles were altered. For each of the four fingers ab/adduction ranged from -15 to 15 degrees; the range of flexion for the knuckles was -50 to 90 degrees; the range of motion for the proximal-middle phalangeal joints was 0 to 120 degrees; and the range of motion for the middle-distal phalangeal joints was 0 to 90 degrees. The metacarpal-trapezium joint of the thumb had a range of -25 to 25 degrees of ab/adduction and -15 to 45 degrees of flexion; the metacarpal-distal phalangeal joint had a range of -45 to 40 degrees; and the distal-proximal joint of the thumb had a range of -75 to 25 degrees.

Masses and inertial values were added to all of the remaining bodies of the model based on rough estimates. The masses and inertial values were not intended to be especially accurate, but were instead used to demonstrate the feasibility of the computational model. A 2-kg ball with a radius of 4 cm was added to the model for the hand to grasp. Spherical contact surfaces for the ball's surface and for various points on the hand were also included. The contact surfaces on the palm included the inside of the knuckles and points near the proximal ends of the metacarpals for all five digits. Contact surfaces were also placed on the inside of each phalangeal bone for each finger. All of the contact surfaces were modeled as being stiff and non-elastic. The coefficients of static and dynamic friction between contact surfaces were modeled as 0.9 and 0.7, respectively.

The desired kinematics for a ball grasp were based on the same adult male subject used to determine the axes of rotation for the remaining finger joints in the model. Initially, all degrees of freedom were assumed to be approximately zero. The final values for finger and thumb joint angles were measured experimentally. Cosine curves were used to map initial and final joint angles. Cosine curves were used to ensure that the system would be modeled as starting from rest and to ensure that second derivatives of angle positions would be non-zero. The total elapsed time for the coordinated ball grasp motion was set as 0.375 seconds. See Figure 1 for images of the initial and final hand positions, and the cosine curve fits used for the angle positions.

Once the above modifications were made to the Stanford VA Model, inverse dynamics analyses were performed in order to investigate the moments required to move generate the desired kinematics. Force estimates for each of the muscles in the hand were also made using a constant muscle activation for all muscles. The observed changes in muscle forces were, therefore, due to changes in contraction velocity, fiber length, and individual muscle properties.

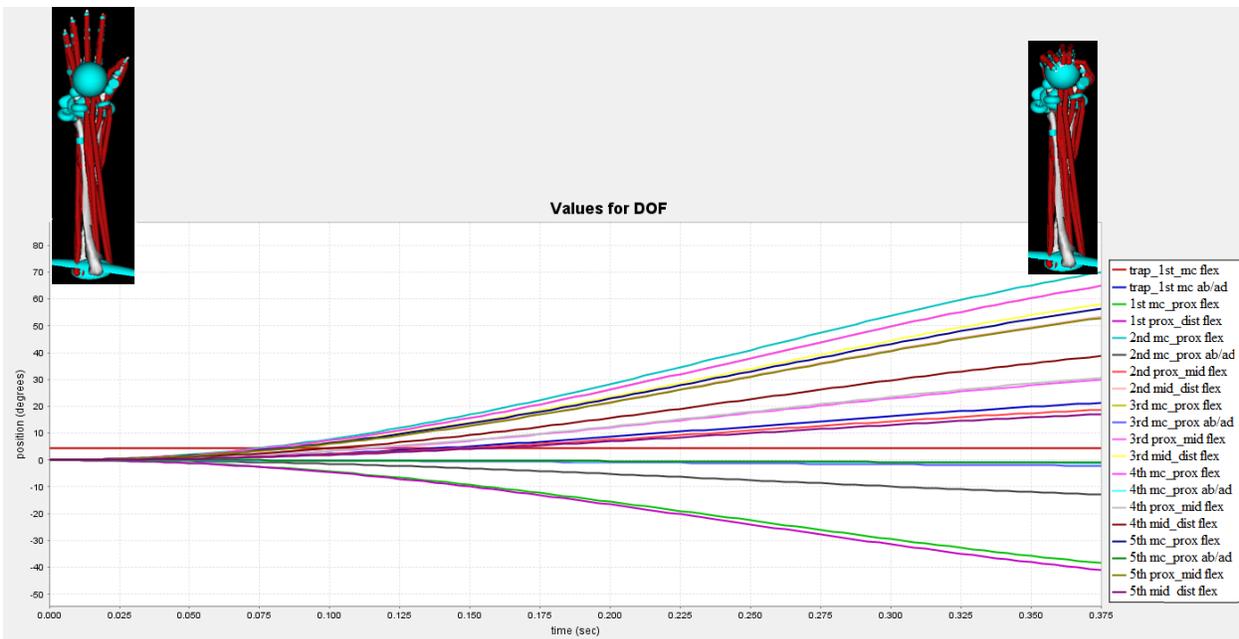


Figure 1. Cosine curve fits for DOF. Trap = trapezium; mc = metacarpal; prox, mid, dist = proximal, middle, and distal phalangeal.

3. RESULTS

The resulting moments from the inverse dynamics analyses are presented in Figure 2. All of the moments were relatively small, with values in N-mm. The moments also generally followed a sinusoidal path, which was expected given the cosine curve fits of the desire kinematics. Also as expected, the moments decreased in magnitude for the more distal joints, as the masses and inertial values of the bodies involved also decreased.

The forces generated using a constant muscle activation are presented in Figure 3. Due to the fact that the wrist was held fixed but the joint was not locked, the extensor muscles for the four fingers had significantly higher magnitude of force than the flexors, despite the fact that the overall motion of the fingers is one of flexion.

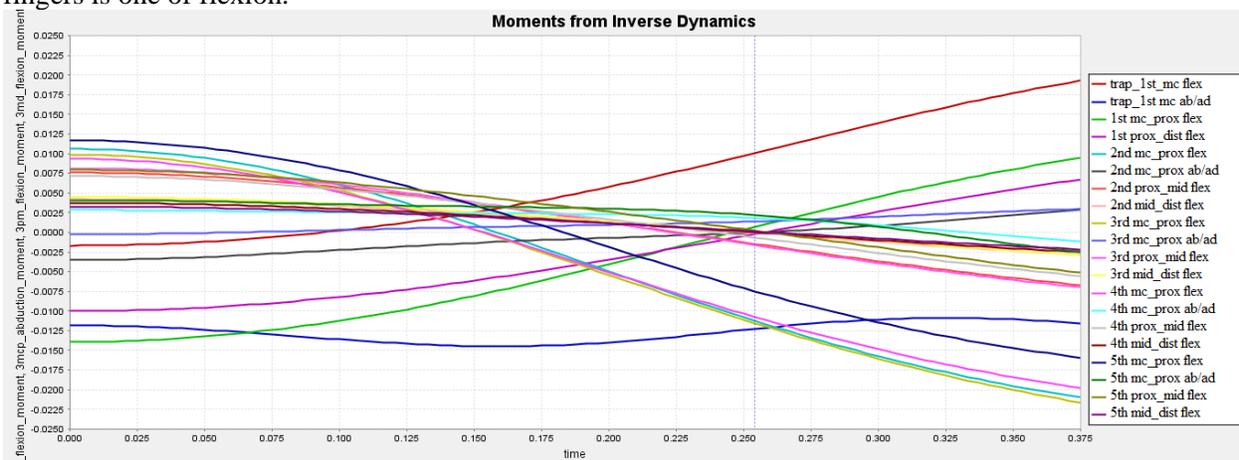


Figure 2. Cosine curve fits for DOF. Trap = trapezium; mc = metacarpal; prox, mid, dist = proximal, middle, and distal phalangeal.

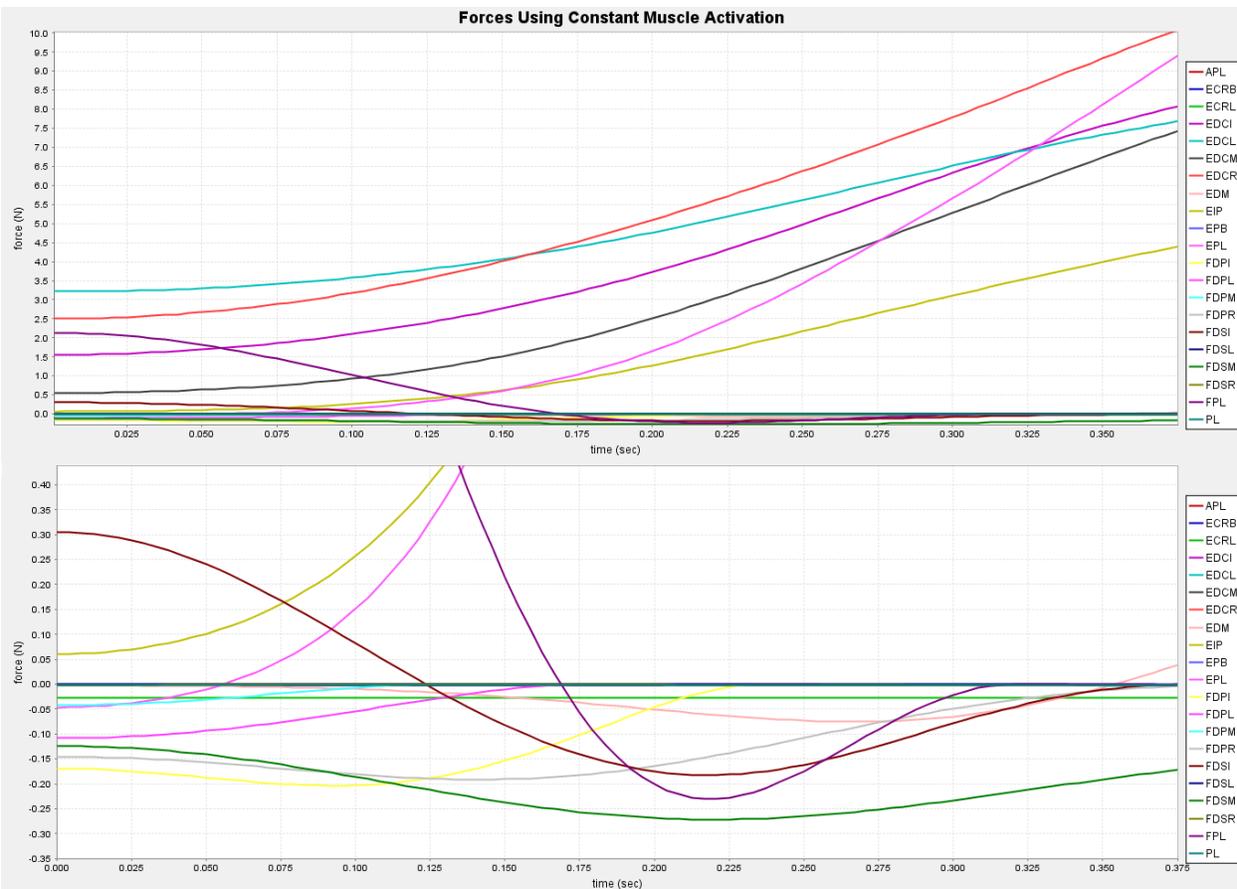


Figure 3. Muscle forces using constant activation.

4. DISCUSSION

Based on the observed moments and forces from the computational model of the natural human hand's ball grasp, several insights can be made which concern the design of a functional hand prosthesis capable of performing the same task. Firstly, and perhaps most importantly, *at least* all of the degrees of freedom used in the computational hand model are required to perform a ball grasp. This implies, that for a five digit functional hand prosthesis, the prosthesis must have at least two degrees of freedom at the knuckles and base of the thumb and one degree of freedom at each of the phalangeal-phalangeal joints. Secondly, flexor and extensor muscles do not work truly opposite each other. This observation is likely due to the fact that the wrist was not locked during the motion and that the extensors had to produce a large amount of force in order to prevent the wrist from going limp. If the functions of wrist flexion and finger extension were de-coupled, the flexion and extension of the fingers could likely be controlled using individual mechanisms for each finger. These would allow for a larger reduction in the complexity and number of mechanisms required overall. Unfortunately, this potential decrease in required mechanisms is mitigated by the fact that all five digits require ab/adduction in order to perform the ball grasp. Specifically, if the fingers are not capable of spreading out as well as flexing, the fingers will not be able to grab the ball and hold the ball in the presence additional external forces such as gravity. Thus, at least a universal joint at the base of each digit is required in order to allow for a minimum of two degrees of freedom. The added requirement of additional degrees also implies the potential need for more mechanisms and mechanical drivers.

The current computational model still has several remaining limitations. Firstly, the masses and inertial values for each of the bodies involved are based only on rough estimates from one subject. These values

would obviously change depending on the material of the prosthesis or the age/size of the subject. Secondly, the contact surfaces between the hand/fingers and the ball were only points. Due to the high stiffness of the contact spheres used, the actual contact between the ball and the hand/finger occurred only at the point at which the contact surface touched. This means that there was no surface area of contact. Obviously, this would not be the case for a natural human hand and likely not be the case for prostheses either. The elasticity of the hand/prosthesis and the ball are essential to the ability to develop the friction forces which would be required in order to solidly grip a ball. Finally, the current model does not take into account the coupled range of motion of the ring finger to the current position of the middle and little finger. In actuality, for the natural human hand, the range of motion of the ring finger is constrained by the current position of the middle and little finger due to the presence of connective tissues. In a hand prosthesis, however, the motions of the individual fingers would likely be de-coupled, as they are in the current model.

Future work on this subject will include the examination of other common hand functions, include the grasping of cylindrical objects (“staff grasp”) and sign language. Ultimately, electromyography (EMG) measurements may be explored in an attempt to perform real-time calling of routine functions, such as a ball or staff grasp, based on the contraction pattern of muscles proximal to the hand.

5. REFERENCES

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