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Capacity of Small Groups of Muscles to Accomplish Precision Grasping Tasks

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Abstract—**An understanding of the capacity or ability of various muscle groups to generate endpoint forces that enable grasping tasks could provide a stronger biomechanical basis for the design of reconstructive surgery or rehabilitation for the treatment of the paralyzed or paretic hand. We quantified two-dimensional endpoint force distributions for every combination of the muscles of the index finger, in cadaveric specimens, to understand the capability of muscle groups to produce endpoint forces that accomplish three common types of grasps—tripod, tip and lateral pinch—characterized by a representative level of Coulomb friction. We found that muscle groups of 4 or fewer muscles were capable of generating endpoint forces that enabled performance of each of the grasping tasks examined. We also found that flexor muscles were crucial to accomplish tripod pinch; intrinsic muscles, tip pinch; and the dorsal interosseus muscle, lateral pinch. The results of this study provide a basis for decision making in the design of reconstructive surgeries and rehabilitation approaches that attempt to restore the ability to perform grasping tasks with small groups of muscles.**

I. Introduction

Neurologic injury, such as spinal cord injury (SCI) or stroke, can substantially impair the ability to perform grasping tasks. Movement deficits can range from an inability to move the hand completely to various levels of impairment affecting hand movement. When movement is possible, compensatory grasp strategies are often employed to interact with the environment. Such strategies sometimes exploit the passive joint range of motion of paretic finger and thumb joints and the resting posture of the paretic hand to trap an object between the fingers, between the fingers and palm, or between the fingers and thumb. While compensatory approaches are serviceable, the ability to grasp objects may be enhanced with greater control over endpoint force generation than currently exists in the paretic or paralyzed hand. Enhanced force control is important to accomplish tasks that require precision grip, such as manipulation of small, thin, delicate or unusually shaped objects.

Rehabilitation and reconstructive surgery have been used to promote functional recovery of grasp, however, outcomes have been mixed. For example, tendon transfers surgery is commonly performed to restore the ability to grasp in persons with cervical SCI. However, restore pinch strength varied by an order of magnitude across patients [1, 2]. Outcomes have been mixed perhaps in part because of a lack of understanding of the contributions of muscles to performing grasping tasks.

The absence of any support in the literature for the incorporation of in-situ measurements of muscle endpoint forces to remediate grasp impairment suggests that intuition plays a role in predicting muscle mechanics. Musculoskeletal mechanics of the hand is complex and not easily predicted from anatomical knowledge. Several previous studies have shown that muscles contribute to endpoint force generation in counter-intuitive ways [3, 4]. For example, thumb flexors do not produce "flexion-directed" or downwardly directed endpoint force during grasping tasks [3]. Further, endpoint force direction varies among uni-, bi- and tri-articular thumb flexors suggesting a complex relationship between muscle articularity and force direction [3]. Finally, a recent study demonstrated that the vast majority of the possible endpoint forces that the index finger produces uniquely depends on the action of one or more muscles [5] challenging the notion of muscle redundancy in control of the finger.

The challenge of restoring the ability to perform grasping tasks is daunting. In many cases, such as with SCI, it is feasible to restore function to only a subset of muscles, e.g., one muscle, a presumed synergic pair or the like to accomplish one specific grasping task [3, 6]. In these cases, it can be argued that precise muscle coordination is less required than in cases where numerous muscles, which produce differently directed endpoint forces [3, 4], must be exquisitely controlled to accomplish a grasping a task. It stands to reason that it would be helpful to know the capacity or ability of small groups of muscles to perform grasping tasks from the standpoint of satisfying endpoint force production requirements. While the chief focus of the study was on small groups of muscles, we examined the performance of large groups of muscles for completeness. Specifically in this modeling study, we addressed the following questions: (1) what grasping tasks are possible with muscle groups of various sizes; and (2) to what degree to do various muscles influence the performance of certain grasping tasks. We considered three grasping tasks—tripod, tip and lateral pinch—that span the range of force directions in which the index finger most commonly produces forces [7].

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II. METHODS

A. Protocol

A cadaver-based model, combined with computational geometry, can provide a starting point for understanding muscle function during the performance of grasping tasks [4]. A cadaver-based model is one in which muscle function is measured directly from cadaveric specimens. Valero-Cuevas et al. [4] measured muscle endpoint forces in 11 cadaveric specimens of the index finger in a functional posture (Fig. 1). The following matrix equation describes the map between the muscle force vector (f_t) and endpoint force vector (f^e):

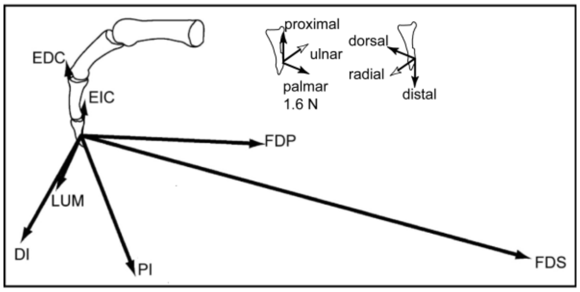

Figure 1: Index Finger Muscle Endpoint Forces. Endpoint forces of index finger muscles produced when each muscle generates maximum isometric force. The posture of the finger was 45 deg flexion at both the metacarpophalangeal and proximal interphalangeal joints and 10 deg flexion at the distal interphalangeal joint. Muscle abbreviations: flexor digitorum profundus (FDP), flexor digitorum superficialis (FDS), extensor indicis proprius (EIP), extensor digitorum communis (EDC), lumbrical (LUM), first dorsal interosseus (DI), first palmar interosseus (PI). Force components: palmar > 0, ulnar > 0, proximal > 0.

$$f^e = Af_t \qquad (1)$$

where

$$f^e = \begin{bmatrix} f^e_{palmer} & f^e_{u\ln ar} & f^e_{proximal} & \tau^e_{extension} \end{bmatrix}^T$$

$$A = \begin{bmatrix} 27 & 68 & -1.08 & -3.04 & -4.8 & 1.6 & -6.8 \\ 9.2 & 18 & 2.4 & 0.64 & -0.76 & -16 & 20 \\ 3.5 & -4.4 & 4.4 & 11 & -10 & -10 & -33 \\ 0.22 & 0.52 & 0.092 & 0.16 & 0.064 & 0.10 & 0.15 \end{bmatrix}$$

$$f_t = \begin{bmatrix} f_{FDP} & f_{FDS} & f_{EIP} & f_{EDC} & f_{LUM} & f_{DI} & f_{PI} \end{bmatrix}^T$$

A is defined as the action matrix and $0 \le f_i \le 1$. The columns of A, scaled from the columns in A reported in Valero-Cuevas et al. [4], are maximum endpoint forces (Newtons) produced by the corresponding element in f_t. These forces are depicted in Fig. 1. For this study, only muscle endpoint forces—and not endpoint torques (last row of A)—were considered.

<u>*Endpoint Force Distributions*</u>

Planar *endpoint force distributions* (also referred to as *feasible force sets* [5]) were computed for muscle groups of every size in the planes of index finger flexion-extension (FE, palmar-proximal plane, Fig. 1) and ab-adduction (AA, ulnar-proximal plane, Fig. 1) using A (EQ. 1). We defined groups of 4 or fewer muscles as small groups; and the remaining groups as large groups. The number of muscles for each designation was partly based on the small number of muscles that hand surgeons manipulate in attempt to restore the ability to perform grasping tasks following cervical SCI [8]. The total number of muscle groups, p, was given by EQ. 2:

$$p = \sum_{n=2}^{m} \binom{m}{n} \qquad (2)$$

where m is the maximum number of index finger muscles (i.e., 7) and n is the number of muscles in a group (i.e., n = 2, 3, 4…7). For this study, p = 120 and the number of muscle groups consisting of 2 muscles was 21; of 3 muscles, 35; of 4 muscles, 35; of 5 muscles, 21; of 6 muscles, 7; and of 7 muscles 1. An endpoint force distribution was determined for each muscle group by finding the convex hull about all possible linear combinations of muscle endpoint forces in the group. The area of the convex hull was computed using *convhull* in MATLAB (MathWorks, Natick, MA).

<u>*Idealized Endpoint Force Distributions*</u>

When the index finger is used to secure an object during tripod, tip and lateral pinch, the finger produces a force chiefly in the palmar, distal, and radial directions (Fig. 2). To understand the capacity of muscle groups to produce endpoint forces in any of those directions, idealized endpoint force distributions (EFDs), centered around the three directions of interest, were created (Fig. 2).

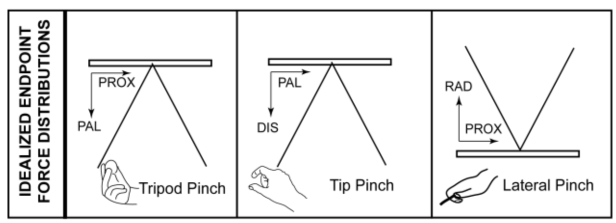

Figure 2: Idealized Endpoint Force Distributions. Idealized endpoint force distributions centered around three endpoint force directions—palmar, distal and radial—that approximate desired fingertip force production requirements for grasp equilibrium during various grasps, e.g., tripod, tip, lateral pinch. Abbreviations: PAL – palmar; PROX – proximal; DIS – distal; RAD – radial.

Each distribution was approximated as a friction cone [9] (Fig. 2) that was projected onto the FE (tripod, tip pinch) or AA (lateral pinch) plane and directed in the palmar, distal or radial direction. Mathematically, each of the 3 distributions was approximated by the Coulomb Friction Law (EQ. 3)

$$|f_T| \le (\tan\theta) f_N \qquad (3)$$

f_N and f_T are the normal and tangential force components, respectively, defined with respect to the contact surface and θ is the angle of friction. To represent a fairly large range of surface properties, θ was set to 30 deg—the approximate angle that corresponds to the pooled results of a study in which static frictional coefficients were computed between the finger/thumb pad and materials including paper, aluminum, suede, tape, vinyl and sandpaper under both dry and moist conditions [10].

B. Data Analysis

Endpoint Force Distribution Characteristics

To compare muscle group EFDs to idealized EFDs, we thought it most logical to use an area-based metric. For each muscle group's EFD, the *overlap index* was computed as the ratio of the area of intersection between the EFD and an idealized EFD, and the area of the EFD (Fig. 3). This particular performance metric was chosen because it

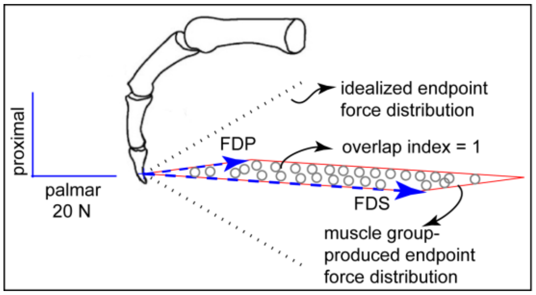

Figure 3: Muscle Group Endpoint Force Distribution and Overlap Index. Modulation of individual muscle endpoint forces generate endpoint force distribution (EFD). Overlap between muscle group EFD and idealized EFD (friction cone) is indicated by gray circles. Overlap index for an example small muscle group is presented.

rewarded muscle groups that produced EFDs that overlapped to a great extent those of the tested grasping tasks and penalized muscle groups otherwise where more precise muscle coordination would be required to accomplish the task. In total, 120 overlap indices were calculated for each of the three idealized EFDs. Quartiles of the overlap index for each idealized EFD were calculated to identify groups of substantial (75th percentile) and minimal (25th percentile) overlap. We viewed the 30 muscle groups whose overlap indices were in the upper quartile range for each grasping task as most likely to satisfy the force production requirements for that task. In contrast, the 30 muscle groups in the lower quartile range were viewed least likely to satisfy force production requirement for a given task.

Realizing that individual muscles may influence differently a muscle group's ability to perform a grasping task, a ranking procedure was used to determine the influence of muscle on overlap indices. Specifically, overlap indices were arranged in tabular form for each set of muscle groups, i.e., 6 tables were created. The differences in entries from tables of consecutive muscle group sets (i.e., 5 difference tables) were computed in such a way to determine the change in index due to individual muscles. The mean index changes for individual muscles were computed between consecutive muscle group sets (between-consecutive-group mean index changes). The overall mean index changes for individual muscles were computed by finding the means of the between-consecutive-group mean index changes for individual muscles. The overall means, representing muscle influence on overlap indices, were ranked.

III. Results

Muscle groups, ranging in size from 2 to 6 muscles, produced EFDs that substantially overlapped with each idealized EFD and therefore were viewed as viable muscle groups for accomplishing tripod, tip or lateral pinch task (Table 1). Within each set of muscle groups (e.g., the set of all 2-muscle muscle groups or 3-muscle muscle groups), the percentage of groups that could accomplish a given pinch task was comparable for tripod and tip pinch tasks, but generally either larger (large groups of muscles) or smaller

Table 1: Instances of Substantial Overlap Between Muscle Group Endpoint Force Distributions and Idealized Endpoint Force Distributions

		1	2	3	4	5	6
2	2	P					
	3	P	P				
	4	/	P	/			
	5	/	P	/	/		
	6	P	P	D, R	R	D	
	7	D	/	D	D	D	D
3	23	P					
	24	P					
	25	P					
	26	P					
	27	/					
	34	/	P				
	35	/	P				
	36	P, R	P, R				
	37	/	/				
	45	/	P	/			
	46	R	P, R	R			
	47	/	/	D			
	56	/	/	D, R	/		
	57	D	/	D	D		
	67	D	/	D	D, R	D	
4	234	P					
	235	P					
	236	P, R					
	237	/					
	245	P					
	246	P, R					
	247	/					
	256	P					
	257	/					
	267	/					
	345	/	P				
	346	/	P, R				
	347	/	/				
	356	R	/				
	357	D	/				
	367	D	/				
	456	R	R	R			
	457	D	/	D			
	467	D, R	R	D, R			
	567	D	/	D	D, R		
5	2345	P					
	2346	P, R					
	2347	/					
	2356	P					
	2357	/					
	2367	/					
	2456	P, R					
	2457	/					
	2467	/					
	2567	/					
	3456	R	R				
	3457	D	/				
	3467	R	R				
	3567	D	/				
	4567	D, R	/	D, R			
6	23456	P, R					
	23457	/					
	23467	/					
	23567	/					
	24567	/					
	34567	D, R	/				
7	234567	/					

Muscle group sizes indicated in vertical areas to left of sub-tables. Muscle groups described by label for muscle combinations in first column and muscles across the top row. For instance, the first 3-muscle group was composed of muscle 2, muscle 3 and muscle 1. Gray areas: redundant or no muscle group. Box with diagonal line: no muscle group overlap. FDP-1, FDS-2, EIP-3, EDC-4, LUM-5, DI-6, PI-7. P-palmar, tripod pinch; D-distal, tip pinch; R-radial, lateral pinch.

(small groups of muscles) for lateral pinch task (Table 2). For example, Table 2 shows that for the set of muscle groups consisting of 2 muscles, 33% of those groups produced EFDs that substantially overlapped with those of tripod and tip pinch tasks, while only 10% substantially overlapped with that for lateral pinch task.

While muscle groups differed in their composition, i.e., there were numerous muscle combinations within each set of muscle groups that accomplished the desired task, certain muscles influenced more than others the extent to which muscle groups could be viable for performing a given grasping task. As it related to the performance of tripod pinch task, flexor muscles (FDP, FDS) (defined in Fig. 1) had the greatest influence; extensor muscles (EIP, EDC), intermediate influence; and intrinsic muscles (DI, LUM, PI), the least influence. Pertaining to the performance of tip pinch task, the order of muscle influence was essentially opposite to that of tripod pinch, i.e., PI, DI, LUM, EIP, EDC, FDP, FDS. To accomplish lateral pinch, muscles were ranked in decreasing order of influence as follows: DI, EDC, EIP, FDP, LUM, FDS, PI.

Table 2: Percentage of Number of Muscle Groups, for Given Muscle Size, that Overlapped with Idealized EFD for Grasping Task

Group size	Tripod (%)	Tip (%)	Lateral (%)
2	33	33	10
3	29	26	20
4	23	23	23
5	19	19	38
6	14	14	29
7			

IV. Discussion

The goal of the study was to understand the capacity or ability of primarily small groups of muscles to accomplish functional grasping tasks, characterized by a representative level of Coulomb friction, and to understand the relative importance of muscles to accomplish those tasks. We explored two questions: (1) what grasping tasks are possible with muscle groups of various sizes; and (2) to what degree do various muscles influence the performance of certain grasping tasks. We found that many combinations of muscles--consisting of 2, 3 or 4 muscles--could accomplish each grasping task examined (as evaluated by the performance index used) (Table 1). Fewer small groups of muscles could accomplish lateral pinch tasks as compared to tripod and tip pinch tasks (Table 2). These results, based on the performance index used, differ from the study by Kutch et al. [5] perhaps because larger deviations in endpoint force away from desired force directions (palmar, distal and radial)—though still consistent with functional task requirements [10]—were considered. Finally, we found that flexor and intrinsic muscles were most and least important, respectively, for muscle groups to accomplish tripod pinch task. Contrarily, the opposite muscle rank-grasping task relationship was true for performing tip pinch. Both results are consistent with Kutch et al. [5]. For lateral pinch, muscles of greater influence as compared to muscles of lesser influence formed endpoint force-based agonist-antagonist pairs, e.g., DI-PI and EDC-FDS. Results from this study could provide a stronger biomechanical basis for the design of grasp restorative treatment interventions following neurologic injury such as stroke or SCI and therefore improve functional outcomes. To the best of our knowledge, this is the first study that determined the relative influence of muscles in the performance of grasping tasks.

This study was not designed to analyze the effectiveness of large groups of muscles to satisfy the endpoint force requirement of grasping tasks. In many cases, fewer large groups of muscles had endpoint force distributions that overlapped with those of the grasping tasks examined (Table 2). This result was an artifact of the performance index used. By design, the overlap index penalized muscle group EFDs which did not almost entirely overlap with the idealized EFD of interest. Heavy overlap, we believe, is a desirable quality that benefits surgical reconstruction of grasp, for example, involving very few muscles. In general, however, careful coordination of a larger group of muscles offers versatility in accomplishing grasping tasks and control over fewer muscles (simulated [4, 11] and actual neurologic deficits [12]) reduces grasping ability. Future studies will examine the robustness of study findings to 3D endpoint force distributions and to other functionally relevant postures of the index finger.

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