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Understanding Forearm Muscle Activity during Everyday Common Grasps: Insights for Rehabilitation, Prosthetic Control, and Human–Machine Interaction

Néstor J. Jarque-Bou *, Margarita Vergara and Joaquín L. Sancho-Bru

Department of Mechanical Engineering and Construction, Universitat Jaume I, 12071 Castellón, Spain; vergara@uji.es (M.V.); sancho@uji.es (J.L.S.-B.)
* Correspondence: jarque@uji.es

Abstract: The specific role of forearm muscles in the development of activities of daily living (ADL) remains unknown. Consequently, studying forearm muscle activity during the most commonly used grasps in ADL would yield valuable insights for hand function evaluation, rehabilitation, and advancements in prosthetic control. In this study, forearm muscle activity was analyzed in 22 healthy subjects, examining seven representative forearm areas during the performance of seven types of grasps at 50% of maximum effort. A Scheirer–Ray–Hare test revealed significant differences for grasp, spot, and their interaction ($\alpha < 0.05$), but not for repetition (and its interactions). Specific significant differences between grasps were found in specific spots by means of Bonferroni post hoc analyses, ensuring the possibility to discriminate between grasps, which is key to identifying the person's intention to perform a particular grasp. The median values ranged from 4.4% to 32.8%, depending on the spot and grasp, with small 95% confidence intervals (0.5% to 5.5%). Cylindrical grasp requires the highest muscle activity among all spots, while lateral pinch demands the least. The findings elucidate the contribution, coordination, and function of each muscle in relation to each grasp, with implications for rehabilitation, prosthetics, and telerobotic and teleoperation systems.

Keywords: electromyography; electrode placement; forearm muscles; myoelectric prostheses; rehabilitation; telerobotics

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1. Introduction

Hand grasp execution comprises two primary stages: reaching for the object and actual grasping. The force required to close the hand around an object is influenced by various factors, including grasp stability (the ability to withstand external forces) and grasp security (resistance to slipping), both of which depend on the grasp configuration [1,2], among other factors. Hand grasping capability relies on the coordination of 32 muscles in the forearm and hand. However, the specific role of these muscles in activities of daily living (ADL) remains unclear. Therefore, examining forearm muscle activity during common grasps used in ADL could provide valuable insights for assessing hand function and rehabilitation. Moreover, such analysis would provide precise information about an individual's movement intentions, which could be beneficial for applications such as telerobotic systems, teleoperation, and prosthetics.

Muscular activity is commonly assessed using electromyography (EMG), which records the electrical activity of muscles. Surface EMG (sEMG) is widely used in controlling prosthetic limbs [3–6], exoskeletons [7,8], rehabilitation devices [9], and telerobotic systems [10–15]. However, sEMG electrodes are placed on the skin surface above the muscle, making the recorded sEMG signal highly dependent on electrode placement and susceptible to interference from adjacent muscles [16]. This issue is particularly significant in the forearm, where 20 muscles overlap [17], making it nearly impossible to isolate the sEMG signal from individual muscles. In a previous study [18], we identified forearm areas with similar muscle activation patterns during a set of standardized ADL, offering a potential method for characterizing muscle activity.

Few studies have examined the role of forearm muscles by investigating their muscle activity [19]. A recent study [19] explored forearm muscle activity during handgrip contractions while simultaneously applying various levels of wrist forces. Their findings corroborated existing literature [20], indicating that wrist extensors functioned as joint stabilizers and that wrist flexors exhibited task-dependent behavior. These results underscore the significance of assessing forearm muscle recruitment across different tasks or grasps. However, the precise role of forearm muscles in hand and wrist tasks such as grasping remains not fully understood [19].

Furthermore, disorders affecting the upper extremities can significantly impair the performance of various muscles, thereby limiting an individual's capacity to carry out basic ADL. Fortunately, there are several approaches aimed at restoring upper extremity functionality. Some robotic devices currently used in clinical practice use sEMG as an input signal, providing insights into the individual's intention to execute specific movements [21]. Therefore, improving our understanding of the role of forearm muscles during grasping could potentially improve existing rehabilitation devices. Additionally, some prosthetic hands worn by amputees use sEMG signals from residual muscles post-amputation [22]. More accurate information about an individual's movement intention can enhance the usability of such prostheses [23].

Teleoperation involves the remote control of a robot/machine by a human operator [24]. One approach is to monitor and replicate the motion and/or forces performed by the operator in the local site. sEMG is commonly employed for this purpose in the control interface for telerobots [25,26]. Therefore, enhancing our understanding of the role of forearm muscles during grasping could contribute to the development of more intuitively controlled hand prostheses and enable more accurate estimations of the operator's intended motions, particularly in the context of rehabilitation, telerobotic systems, and teleoperation.

This study examines the contribution of forearm muscles to grasp performance by recording muscle activity using sEMG in seven representative forearm areas [18] during the performance of seven representative grasps. Consequently, the investigation delves into the contribution, coordination, and roles of each muscle in relation to various grasps, along with their implications for rehabilitation, prosthetics, telerobotics, and teleoperation.

2. Materials and Methods

2.1. Experiment Description

Twelve males and ten females, aged on average 35 ± 9 years, were included in the study. Selection criteria ensured gender balance in the dataset, ages ranging from 20 to 65 years, and no reported upper limb pathologies. Prior to participation, all subjects gave their informed written consent for the study, which was approved by the ethics committee of our university (reference number CD/31/2019). Participants performed seven representative grasps of ADL (Figure 1), based on the grasp taxonomy by Vergara et al. [27]: two and three fingers pad-to-pad pinch (PpP), cylindrical grasp (Cyl), lumbrical grasp (Lum), lateral pinch (LatP), oblique palmar grasp (Obl), and intermediate power-precision grasp (IntPP).

Muscle activity was recorded using an eight-channel sEMG device from Biometrics Ltd., sampling at 1000 Hz. Integral dry reusable sEMG electrodes (SX230) were employed, featuring a gain of 1000, a bandwidth ranging from 20 Hz to 460 Hz, and noise levels below 5 μV. Grasp effort was measured using hand grip and pinch dynamometers (Figure 2) also from Biometrics Ltd. Signals from the sEMG electrodes and dynamometers were synchronized using the provided Biometrics software version 11.02.

The sEMG electrodes were positioned using a grid drawn on the forearm, guided by five easily identifiable anatomical landmarks. Subjects were seated comfortably with their elbow resting on a table, their arm flexed at a 90° angle relative to the forearm, and the palm of the hand facing them. The grid defined 30 different spots covering the entire forearm surface (Figure 3). The electrodes were placed in the center of seven of these spots, based on the spot groups obtained in a previous work [18] (Figure 3, Table 1), and were set out in a longitudinal direction. Before placing electrodes, hair was removed by shaving and the skin was cleaned with alcohol.

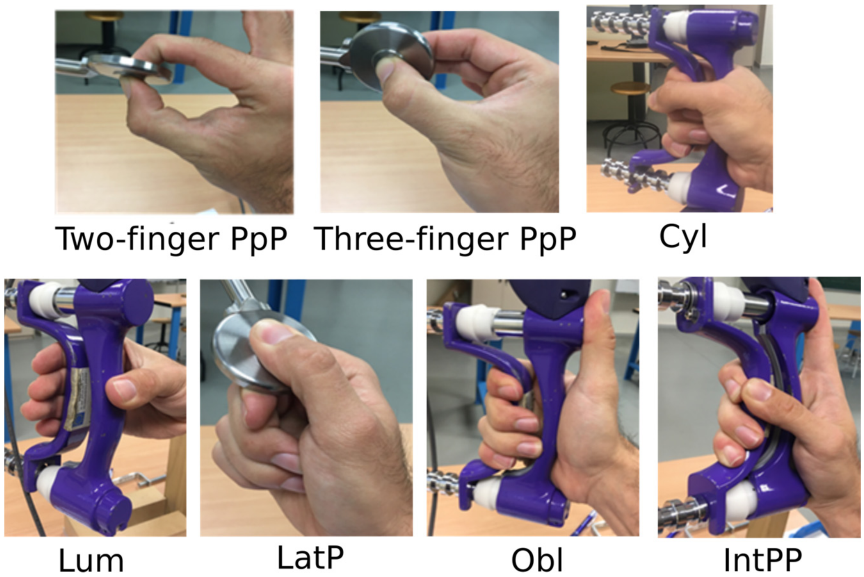

Figure 1. Seven grasps, performed using hand grip and pinch dynamometers.

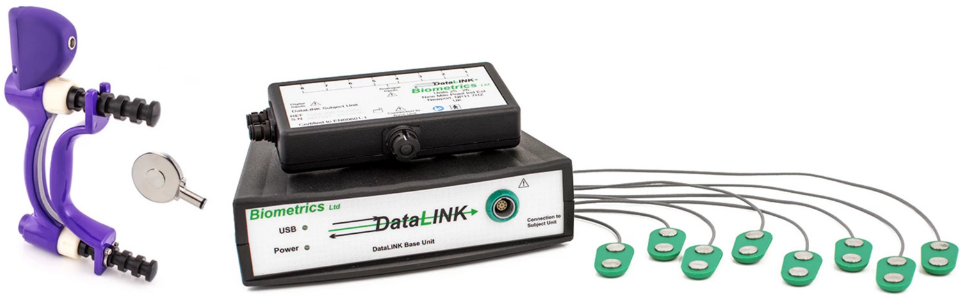

Figure 2. Hand grip and pinch dynamometers, sEMG electrode (SX230) (Biometrics Ltd., Newport, UK) and eight-channel sEMG Biometrics Ltd. devices, (Newport, UK).

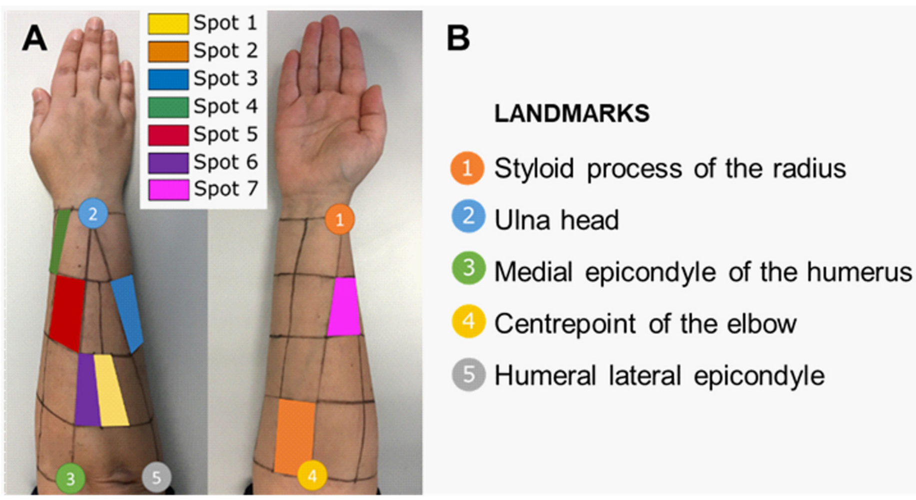

Figure 3. (**A**) Grid and spot areas selected for sEMG recordings. (**B**) Five anatomical landmarks used for grid drawing.

Table 1. Possible underlying muscles beneath each recorded spot, as indicated by a previous work [18].

Scheme	Spot Muscles
1	Flexor carpi ulnaris (FCU)
2	Flexor carpi radialis (FCR), palmaris longus (PL)
3	Flexor digitorum superficialis (FDS), profundus (FDP), and flexor pollicis longus (FPL)
4	Abductor pollicis longus (APL), extensor pollicis longus (EPL) and brevis (EPB)
5	Extensor digitorum communis (EDC)
6	Extensor carpi ulnaris (ECU)
7	Brachioradialis (BR), pronator teres (PT), and extensor carpi radialis (ECR)

Then, subjects performed the seven grasps with the right hand following precise instructions from the operator: the subject was asked to hold a dynamometer simulating the grasp to be analyzed, with the arm aligned with the trunk and the forearm flexed 90 degrees relative to the arm. They were instructed not to exert force initially and then to exert maximum effort while maintaining this posture for three seconds. To prevent unnecessary muscle contractions, the subjects were asked to then progressively increase the effort during 3 s, until they reached 50% of the previously recorded maximum effort with the dynamometer, maintain it for 3 s, and then gradually decrease it back to rest (Figure 4). Each grasp was repeated three times consecutively (only the 50% of the maximum effort), with a 3 min break between repetitions to avoid muscle fatigue. Subjects were allowed to practice each grasp as many times as necessary before recording.

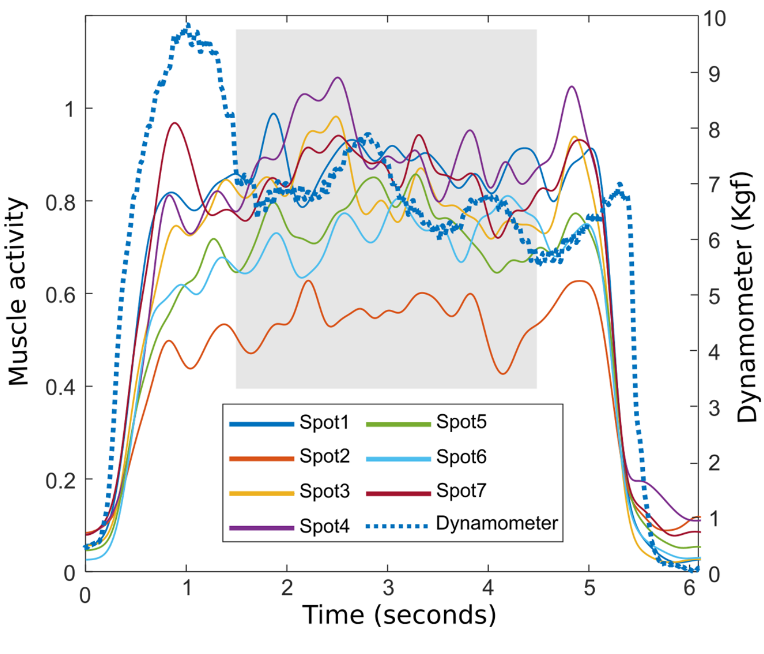

Figure 4. Example of the experiment. Each line corresponds to the measurement of the muscle activity of each spot for one subject during the grasping activity. The grey square corresponds to the 3 s used in the subsequent analyses.

In order to obtain the muscle activity, sEMG signals were normalized using seven records of maximum voluntary contraction (MVC) measured for each subject before performing the grasping efforts: flexion and extension of the wrist, flexion and extension of the fingers, pronation of the forearm, ulnar deviation of the wrist, and elbow flexion. Subjects were instructed to exert maximum effort with the muscles of the forearm and hand while maintaining the same comfortable posture. Rest intervals of 1 min were incorporated between each MVC to prevent muscle fatigue. Rest intervals, repetitions, and trial duration were decided following guidelines from the literature [28,29].

2.2. Data Analysis

The following statistical analyses were conducted using MATLAB® 2023b and SPSS v26 software. The sEMG records underwent several processing steps: they were filtered with a 4th-order bandpass filter between 25–500 Hz, rectified, filtered by a fourth-order low pass filter at 8 Hz, and smoothed using Gaussian smoothing [30]. Muscle activity was determined by normalizing the sEMG records with the maximal values obtained in any of the seven records of MVC measured. For each record, the average of the sEMG values during the three seconds in which 50% of the maximum effort was performed was computed for each spot (50 V). Boxplots were generated for each grasp, and data outliers were eliminated.

A Shapiro–Wilk test was conducted to assess the distribution normality of all the 50 V values, revealing a deviation from normality. Consequently, a Scheirer–Ray–Hare test was conducted ($\alpha < 0.05$) with 50 V as the dependent variable, and grasp, spot, repetition, and their interactions as factors. For post hoc analysis, Kruskal–Wallis tests ($\alpha < 0.05$) were conducted with factors that were significant in the Scheirer–Ray–Hare test.

The 50 V values from the three repetitions of each grasp for each spot and subject were averaged (A50V). Next, the median across subjects of these A50V values (mA50V) were computed for each spot and grasp. To interpret the results, mA50V values for the seven spots across different grasps were represented using polar diagrams, along with the 95% confidence interval (95% CI) across subjects. Finally, the contribution and role of each muscle to each grasp were analyzed and discussed. The data are available at (https://doi.org/10.5281/zenodo.8064019, accessed on 21 March 2024) and have been already used to show the intra and inter-subject variability of several sEMG characteristics in [31].

3. Results

The Scheirer–Ray–Hare test revealed significant differences for grasp, spot, and their interaction ($\alpha < 0.05$). However, repetition and interactions with other factors were not significant ($\alpha > 0.8$). Therefore, in order to look for spots and grasps with significantly different muscle activity, Bonferroni post hoc analyses were conducted, as well as fourteen Kruskal–Wallis analyses, with A50V as the dependent variable: seven (one per spot) with grasp as factor, and other seven (one per grasp) with spot as factor (notice that averaged values across repetitions were used since repetition was not significant). All Kruskal–Wallis analyses per spot were significant ($\alpha < 0.05$) for the grasp factor, and all Kruskal–Wallis analyses per grasp were significant ($\alpha < 0.05$) for the spot factor.

Tables 2 and 3 summarize the results of all the Bonferroni post hoc analyses. Overall, the spots tended to present similar values to each other (Table 2), regardless of the type of grasp. However, there was one exception, spot 2 during IntPP grasps, which exhibited significantly different values compared to all other spots. Upon closer examination of each spot, two main patterns emerged, depending on the kind of grasp: power or precision. During precision grasps (two/three-finger PpP, Lum grasp, and LatP) the wrist and finger flexors (spots 1, 2, and 3) displayed similar values, as did the wrist extensors, finger extensors, and thumb muscles (spots 4, 5, 6, and 7). In power grasps (Cyl, Obl and IntPP grasps), the wrist ulnar deviators exhibited similar activation levels (spot 1 and 7), while the thumb muscles (spot 4) acted similarly to the finger muscles (flexors and extensors, spot 3 and 5) and the wrist extensors and ulnar deviators (spots 6). In other words, antagonistic muscles, such as flexors and extensors, were activated similarly to provide a stable and secure grasp.

Table 2. Result of the Bonferroni post hoc analyses for each grasp. The numbers denote the spots that present similar activation levels (those without significant differences ($\alpha < 0.05$)).

Grasp/Spot	1	2	3	4	5	6	7
Two-fingers PpP	2, 3, 4, 5, 7	1, 3	1, 2	1, 5, 6, 7	1, 4, 6, 7	4, 5, 7	1, 4, 5, 6
Three-fingers PpP	2, 3, 4, 7	3	1, 2, 4	1, 3, 7	6, 7	5, 7	1, 4, 5, 6
Cyl grasp	3, 4, 6, 7	5	1, 4, 5, 6, 7	1, 3, 5, 6, 7	3, 4, 6	1, 3, 4, 5	1, 3, 4
Lum grasp	2, 3, 4, 5, 6	1, 3, 4	1, 2, 4, 5, 6	1, 2, 3, 5, 6, 7	1, 3, 4, 6, 7	1, 3, 4, 5, 7	4, 5, 6
LatP	1, 2, 4, 6	1, 3	1, 2	1, 5, 6, 7	4, 6, 7	1, 4, 5, 7	4, 5, 6
Obl grasp	3, 4, 5, 6, 7	4, 5	1, 4, 5, 6, 7	1, 2, 3, 5, 6	1, 2, 3, 4, 6, 7	1, 3, 4, 5, 7	1, 3, 5, 6
IntPP grasp	4, 5, 6, 7	-	4, 5, 6, 7	1, 3, 5, 6, 7	1, 3, 4, 6, 7	1, 3, 4, 5, 7	1, 3, 4, 5, 6

Table 3. Result of the Bonferroni post hoc analyses per spot. The numbers denote the spots with significant differences ($\alpha < 0.05$) between grasps.

Grasp	Two-Fingers PpP	Three-Fingers PpP	Cyl Grasp	Lum Grasp	LatP	Obl Grasp	IntPP Grasp
Two-fingers PpP		-	1, 2, 3, 7	-	6	1, 2, 3, 7	1, 3, 7
Three-fingers PpP			1, 2, 3, 4, 7	6	6	1, 3, 7	1
Cyl grasp				1, 2, 3, 4, 6, 7	1, 2, 3, 4, 6, 7	7	3
Lum grasp					-	1, 3, 6	1
LatP						1, 2, 3, 6	1, 2, 3, 6
Obl grasp							-
IntPP grasp							

Table 3 shows spots with significant differences between grasps. Four cases presented no spots with significant differences: two-finger PpP versus three-finger PpP and Lum grasp, Lum grasp versus LatP, and Obl grasp versus IntPP grasp. On the contrary, Cyl grasp versus Lum grasp and LatP showed significant differences in almost all spots. Spot 5 did not exhibit significant differences between any grasps.

Table 4 and Figure 5 show the mA50V and 95% CI of each spot during each grasp performed. The median values ranged from 4.4% (spot 3, lateral pinch) to 32.8% (spot 7, cylindrical grasp). Ranges of 95% CI varied between 0.5% (spot 3, two-finger pad-to-pad pinch) and 5.5% (spot 1, intermediate power-precision grasp). Spot 2 exhibited consistently low mA50V and 95% CI values across all grasps. Cyl grasp required the highest muscle activity among all spots, while LatP demanded the least.

Table 4. mA50V and 95% CI values of each spot during each grasp performed. Values are presented in %, with respect to the MVC.

		Spot						
		1	2	3	4	5	6	7
Two-finger PpP	mA50V	9.9	5.1	5.7	15.3	15.1	20.1	15.5
	95% CI	2.1	1.1	0.5	4.0	2.1	3.5	2.1
Three-finger PpP	mA50V	10.9	6.6	9.8	14.1	20.0	26.2	18.3
	95% CI	2.6	1.4	1.3	3.3	4.7	4.2	1.8
Cyl	mA50V	30.5	14.7	25.1	25.6	21.7	24.2	32.8
	95% CI	3.0	2.5	3.6	4.7	4.3	2.9	4.3
Lum	mA50V	9.7	8.0	9.3	13.5	16.4	13.0	20.6
	95% CI	2.0	1.8	2.1	3.0	3.1	2.8	2.6
LatP	mA50V	7.2	5.3	4.4	12.6	14.3	10.7	20.1
	95% CI	1.3	0.9	0.8	0.7	1.8	2.4	2.0

Table 4. *Cont.*

		Spot						
		1	**2**	**3**	**4**	**5**	**6**	**7**
Obl	mA50V	24.1	13.5	23.4	19.3	19.7	22.5	30.9
	95% CI	4.4	2.5	4.0	3.8	4.0	4.1	4.2
IntPP	mA50V	29.2	9.3	18.2	17.6	19.8	19.7	24.4
	95% CI	5.5	1.8	3.8	4.8	4.4	3.0	3.8

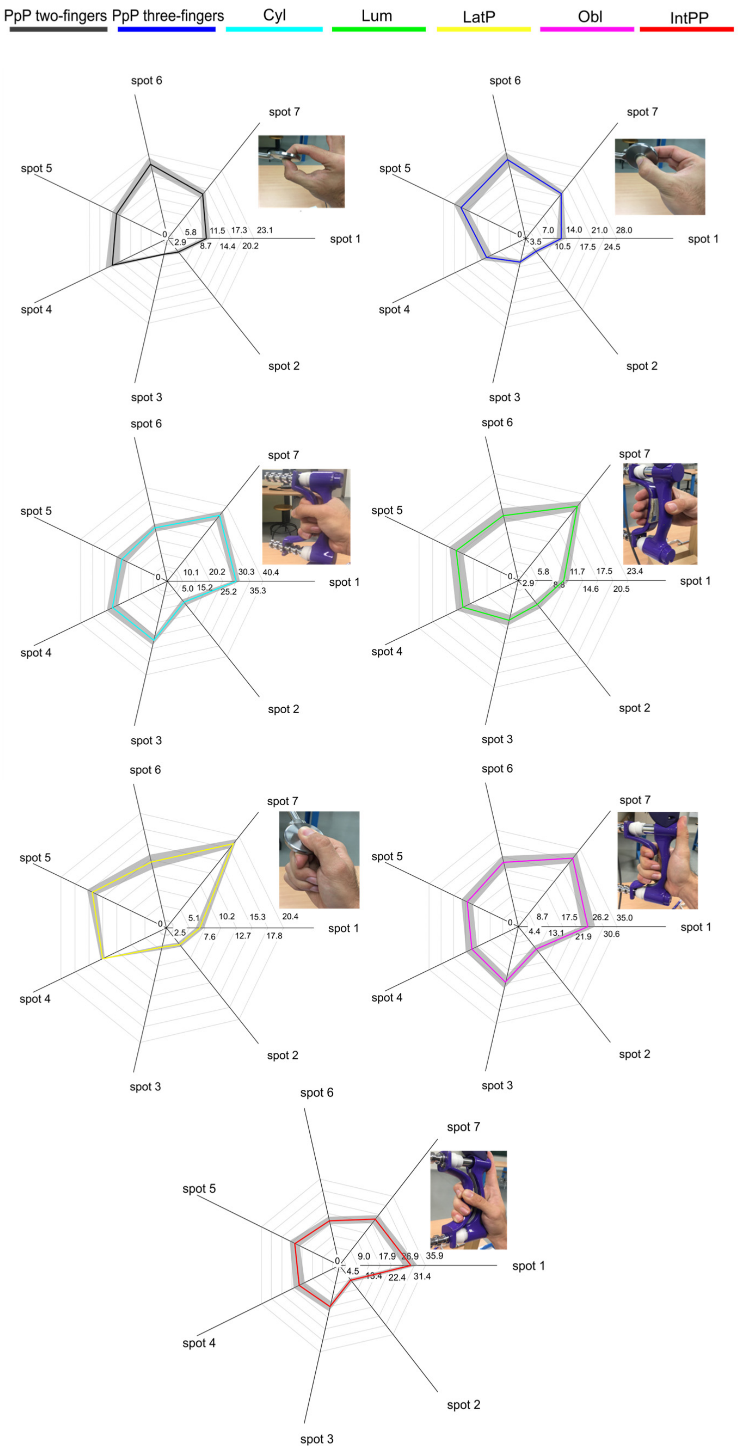

Figure 5. mA50V (%) and 95%CI values obtained for each spot area and grasp, represented using polar diagrams.

4. Discussion

In this study, forearm muscular activity during grasp performance was studied from the recordings on seven representative forearm areas. Our results were consistent with previous findings [20], confirming that wrist extensors acted as joint stabilizers, and that the wrist flexors demonstrated clear task-dependency. However, our results extend beyond this by enabling a deeper exploration of both muscular contributions and the varying coordination among these muscles. The narrow confidence interval of median values across subjects facilitates a general interpretation of the role of these muscles/spots during grasps. Moreover, the significant differences observed among all spots during grasps, as well as between grasps for each spot, provide insight into the contribution of these muscles to grasping and their coordination across different grasps.

4.1. Muscle Contribution

From the results, we observe certain associations between recorded areas/muscles and grasps. Broadly speaking, wrist extensors showed the highest activation levels across all grasps, while wrist flexors also exhibited significant activation, acting as synergistic muscles. Furthermore, when comparing both wrist extensors, the ECR presented higher muscle activity, which could highlight the predominance of a radial deviation during these grasps, probably to counteract the gravitational force exerted to keep the wrist in the grasping position. Finger flexors were highly activated during cylindrical and oblique-palmar grasps, but we also found high level of contraction of the finger extensors, indicating their role as synergistic muscles. Thumb muscles showed higher activation during grasps involving thumb opposition (cylindrical, pad-to-pad pinch and lumbrical grasps). It is worth noting that the main distinction between two-finger and three-finger pad-to-pad pinches was that, in the latter case, the thumb muscles exhibited values more similar to finger flexors. Spot 2 (FCR) showed the lowest muscle activity during the performed grasps. Nevertheless, it could play a crucial role in distinguishing between various power grasps. Although no spot showed significant differences between the oblique-palmar and intermediate power-precision grasps (Table 3), spot 1 and spot 2 displayed different behaviors between these grasps: spot 2 seemed to be more associated with the thumb muscles and finger extensors in the oblique-palmar grasp, while, in the intermediate power-precision grasp, it demonstrated different values, compared to other spots (Table 2). FCU (spot 1) played a key role in distinguishing between the intermediate power-precision grasp and the three-finger pad-to-pad pinch, as well as lumbrical grasp, while ECR (spot 6) was crucial in distinguishing between the lateral pinch and the two/three-finger pad-to-pad pinch, as well as the lumbrical grasp and the three-finger pad-to-pad pinch. The ECU (spot 7) and finger flexors (spot 3) were crucial in distinguishing between the cylindrical grasp and the oblique palmar grasp, and between the cylindrical and intermediate power-precision grasps, respectively.

Table 5 summarizes the primary findings, regarding which muscles were most activated during each kind of grasp. FCU (spot 1), FDS, FDP, and FPL (spot 3) and ECU, BR, and PT (spot 7) presented the highest activity levels during the cylindrical, intermediate power-precision, and oblique-palmar grasps. This observation was in accordance with the existing literature [32], as FCU has been identified as responsible for stabilizing the wrist during activities such as slicing meat (intermediate power-precision grasp) and using a hammer (cylindrical and oblique-palmar grasps). The FDS, FDP, and FPL muscles are finger flexors [33] and these power grasps require flexion of metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints of the fingers, together with the thumb joints. The BR, PT, and ECR act as wrist extensors and radial deviators [34], appearing to function as wrist stabilizers during power grasps, acting as antagonists to the FCU (spot 1).

Table 5. Summary of findings regarding muscles that are more activated and their respective roles in each grasp.

Grasps	Observation about Role of Muscles	Muscles More Activated
two-finger PpP	Thumb abductors and extensors play a crucial role in stabilizing the grasps by counteracting the forces generated by the index finger.	ECU, EDC, BR, PT, ECR
two-finger PpP	The action of the middle finger increases the maximum force generated while reducing the activity of the thumb abductors and extensors.	ECU, EDC, BR, PT, ECR
Cyl	The most powerful grasp. It involves FCU and ECR to stabilize the wrist. Finger flexors and thumb extensors and abductors exert similar and maximum activity.	BR, PT, ECR, EDC, FCU, FDS, FDP, FPL, APL, EPL, EPB
Lum	ECR and ECU are required to extend the wrist. Finger and thumb extensor act to extend the fingers (PIP and DIP joints).	BR, PT, ECR, EDC, ECU
LatP	Presents low activity from all the extrinsic muscles. Extensors are more active than flexors in stabilizing the wrist for grasp execution. The thenar and intrinsic muscles are the primary contributors to grasp force (up to 80%) [35].	BR, PT, ECR, EDC
Obl	Behavior similar to Cyl grasp but thumb placement reduces its muscular contribution.	BR, PT, ECR, FCU, ECU, EDC, FDS, FDP, FPL APL, EPL, EPB
IntPP	FCU and ECR presents maximum forces to stabilize the wrist. Finger flexors and extensors require similar activity.	FCU, APL, EPL, EPB, BR, PT, ECR, EDC

FCR and PL (spot 2) were the muscles with the least muscle activity throughout all the grasps, with the highest value for the cylindrical grasp. According to the literature, FCR is more activated when simultaneously performing a movement of flexion and radial deviation of the wrist [32]. In this case, the grasps considered did not require the wrist exerting any flexion–radial torque, so no activation higher than 20% was observed. Lateral pinch exhibited low activity in all extrinsic muscles, likely due to the significant contribution of the thenar and intrinsic muscles, which account for up to 80% of the grasp force [35].

EDC (spot 5) and APL, EPL, and EPB (spot 4, thumb muscles) presented high activity values during all grasps, with the highest values during the power grasps. EDC is the extensor muscle of the MCP joints of the fingers and also contributes to the extension of the DIP and PIP joints of the fingers, along with the lumbricals and interossei [32]. APL and EPB participate in the abduction and extension of the thumb carpometacarpal (CMC) joint while EPL functions as an extensor and adductor of the thumb MCP joint [34]. An outcome of this study suggests that, during grasps, these muscles also act as antagonists to the finger flexors, counteracting the required flexor moment and ensuring adequate stabilization. This is particularly crucial during precision grasps [36], as the thumb is typically abducted and/or extended during these grasps, engaging in thumb opposition.

ECU (spot 6) presented maximum activity during the cylindrical grasp, two/three-finger pad-to-pad pinch, and oblique-palmar grasp. ECU has the largest moment for ulnar deviation and is an effective wrist extensor only in supination [34]. In these grasps, which require considerable effort from the finger flexors, ECU seemed to play a crucial role in stabilizing the wrist and fingers. By doing so, it countered the moment exerted by the finger and wrist flexors, contributing to the overall stability of the grasps.

An application of the results could be to aid in identifying the key muscles required during each grasp. This could help focus on enhancing the muscular capacity of those muscles or spots that contribute most to each grasp, either through specific exercises or electro-stimulation. For example, to increase the strength of power grasps, which are essential in ADLs requiring more force, such as using a hammer, it is not enough to stimulate the flexors; it is also necessary to stimulate the extensors, which act as antagonists to stabilize the grasps [32]. Furthermore, the mean values obtained from each forearm spot could be used as normative values of muscle activity for a global population, which will illuminate the demand required for common tasks, thus providing baselines for evaluating clinical populations. Another potential application could be to assist in hand function assessment, as these results enable us to evaluate the impact of certain muscles on different types of grasps, by considering their relevance for personal autonomy [37].

4.2. Muscle Coordination

The results revealed synergistic functioning of muscles, some of which were shared between different grasps, as follows:

1. During power grasps, there was coordination between the wrist flexors and extensors. In particular, wrist flexors and ulnar deviators (spot 1) and wrist extensors and radial deviators (spot 7) worked together as synergistic muscles [32] to keep the wrist in a stable position. Finger flexors (spot 3) demonstrated coordination with the finger extensors (spot 5) and thumb muscles (spot 4).
2. Precision grasps involved coordination between the wrist and finger flexors (spots 1, 2, and 3), as well as the wrist extensors, finger extensors, and thumb muscles (spots 4, 5, 6, and 7).
3. The FCR (spot 2) primarily worked alone during power grasps with low activity levels. During precision grasps, the FCR collaborated with the finger flexors (spot 3) to contribute to thumb abduction movements.
4. Generally, thumb muscles (spot 4) coordinated with finger extensors (spot 5).
5. Finger extensors (spot 5) were consistently required with similar activation levels, independently of the grasp performed.

However, apart from these synergistic behaviors, there were specific and significant differences between grasps in specific spots (Tables 2 and 3), which may help to discriminate between grasps, providing more accurate information about the person's intention to perform a particular movement. This is key to improving the control of actual prostheses and robotic devices used in rehabilitation. For example, to distinguish between cylindrical and intermediate power-precision grasps, there was a difference in spot 3 (finger flexors). In the case of the cylindrical grasp, it showed more coordination with spot 1 and required more muscle activity. Another example is distinguishing between precision grasps, which relied on spot 6 (wrist extensors and radial deviators). During the three-finger pad-to-pad pinch, spot 6 exhibited similar values, but only with wrist and finger extensors. However, during the lumbrical grasp, it also appeared more coordinated with the finger flexors, and, during the lateral pinch, with the thumb muscles. Additionally, the three-finger pad-to-pad pinch required a higher activity level than the lumbrical grasp and the lateral pinch.

There were some pairs of grasps where there were no significant differences among any spots. However, different coordination between spots did appear, which could allow for distinguishing between them. For example, between the two-finger pad-to-pad pinch and the lumbrical grasp, the finger flexors seemed more prone to coordinating with the wrist flexors during the two-finger pad-to-pad pinch, whereas, during the lumbrical grasp, apart from coordinating with the wrist flexors, they also showed similar values to the thumb muscles and wrist and finger extensors.

5. Conclusions

We conducted an analysis of the contribution of seven forearm spots during the performance of various types of grasps representative of ADL. This investigation provided valuable insight into the contribution, role, and coordination of these muscles/spots during these grasps.

The results highlight the potential utility of using sEMG to discriminate between different types of grasps. However, it becomes less relevant if this discrimination capability cannot be achieved in real time, as it compromises the practical applicability and usability of the technology. This capability could lead to the design of more intuitively controlled hand prostheses and improve the estimation of the operator's intended motions in teleoperation and telerobotic systems; by defining forearm spots for placing sEMG electrodes, it is possible to provide more accurate information about the intention of the person to perform a particular movement. Additionally, the possibility of integrating other sensors, such as piezoresistive sensors, capacitive sensors, inertial sensors, etc., could help obtain even more robust and precise information. In the same way, these forearm spots could be used to increase the muscular capacity of those muscles/spots that contribute most to each grasp, either through specific exercises, or through electro-stimulation.

Further studies should focus on measuring specific forearm muscles using intramuscular EMG, and including intrinsic muscles. Moreover, future studies should consider exploring other sEMG parameters beyond signal amplitude alone. The study's primary limitation lies in the wrist positioning during grasping performance, since changing wrist posture during the same grasps may lead to different muscle activity results for the wrist muscles. Thus, future research efforts should also focus on controlling and measuring wrist posture more rigorously during grasp performance.

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