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Grasp Analysis in the Home Environment as a Measure of Hand Function After Cervical Spinal Cord Injury

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Abstract

Background. Following a spinal cord injury, regaining hand function is a top priority. Current hand assessments are conducted in clinics, which may not fully represent real-world hand function. Grasp strategies used in the home environment are an important consideration when examining the impact of rehabilitation interventions. *Objective*. The main objective of this study is to investigate the relationship between grasp use at home and clinical scores. *Method*. We used a previously collected dataset in which 21 individuals with spinal cord injuries (SCI) recorded egocentric video while performing activities of daily living in their homes. We manually annotated 4432 hand-object interactions into power, precision, intermediate, and non-prehensile grasps. We examined the distributions of grasp types used and their relationships with clinical assessments. *Results*. Moderate to strong correlations were obtained between reliance on power grasp and the Spinal Cord Independence Measure III (SCIM; $P < .05$), the upper extremity motor score (UEMS; $P < .01$), and the Graded Redefined Assessment of Strength Sensibility and Prehension (GRASSP) Prehension ($P < .01$) and Strength ($P < .01$). Negative correlations were observed between the proportion of non-prehensile grasping and SCIM ($P < .05$), UEMS ($P < .05$), and GRASSP Prehension ($P < .01$) and Strength ($P < .01$). *Conclusion*. The types of grasp types used in naturalistic activities at home are related to upper limb impairment after cervical SCI. This study provides the first direct demonstration of the importance of hand grasp analysis in the home environment.

Keywords

cervical spinal cord injury, hand grasp, egocentric video, SCIM, GRASSP, UEMS

Introduction

Upper limb function is the top priority for recovery reported by people with cervical spinal cord injuries (SCI).[1,2] This arises because many behaviors related to activities of daily living (ADLs) and self-care crucial to preserving independence—such as feeding, dressing, bathing, and grooming—require a functional hand to interact with the environment. Human hand function is notable for the diversity and complexity of the manipulations that can be performed. For example, chopping food with a knife requires employing various grasps during reaching and grasping phases with different temporal and spatial variations.

Precise hand function measurement can support the development of effective rehabilitation strategies and tailored intervention plans to facilitate recovery.[3,4] Multiple tools to evaluate hand function have been suggested in the literature, such as the Sollerman Hand Function Test,[5] the Jebsen–Taylor Hand Function Test,[6] and GRASSP.[7] In the framework of the International Classification of

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Functioning, Disability and Health, these approaches evaluate hand function capacity, which is the ability to accomplish standardized activities in a controlled environment, as opposed to performance, which is how a person completes tasks in their usual environment.[8] For example, grasp choice heavily relies on object properties such as shape, weight, orientation, and on environmental constraints,[9-11] such that observations in the clinic may not fully reflect the challenges experienced in a natural context. Numerous studies in the last few years have examined the relationship between capacity and performance for various cohorts, notably stroke and Parkinson's disease, showing that capacity improvements may not translate to performance improvements.[12-14] To date, accelerometry has been the most commonly used method to measure the performance domain of upper limb function.[12-14] Unfortunately, wrist-worn accelerometers are unable to provide information on the quality of hand movements, such as grasp types.

With the advent of wearable cameras (ie, egocentric video) and smart glasses, we may capture lifelogging first-person video. These recordings offer a new route for studying hand function in non-clinical settings.[15-19] Wearable cameras are commercially accessible, user-friendly, and have proven viability for use in rehabilitation settings.[19,20] The contextual information provided by video sensors enables the identification of hand-object interactions and the analysis of functional hand grasps.

Examining the choice of grasp type is critical to measuring hand performance because it can reflect grasp force, hand and forearm muscle activation, and fine motor control.[21,22] In a power grasp, for example, the extensor and flexor groups of muscles, or extrinsic muscles, are active, whereas, in a precision grasp, intrinsic muscles play an essential part in generating forces.[23,24] With paresis in the hand, one may utilize 1 grasp more frequently than the other to compensate for decreased muscle strength or dexterity.[25] For example, stroke survivors with more severe impairments are more prone to use palmar-digital grasp configurations than those with less severe impairments or healthy people.[25] Grasp duration is another metric relevant to obtaining a comprehensive picture of hand function.[26] For example, using power for an extended period of time may indicate hand strength.

The aim of this study was to analyze the proportions of 4 main grasp types: power, precision, intermediate, and non-prehensile grasp, which are employed by individuals with cervical SCI in their home environments using egocentric video recordings. We hypothesized that these proportions would correlate with the level of impairment, as measured using established clinical assessments. To the best of our knowledge, this is the first effort to employ hand grasp analysis in a naturalistic setting for individuals with SCI. The first contribution of this work is to demonstrate the strong link between hand grasp choice at home and clinical scores, providing new insights into the relationship between capacity and performance. The second contribution is to establish the importance of including non-prehensile grasps in grasp classification analyses after SCI.

Method

Participants

The dataset used in the study was collected in a previous study; its specifics are discussed in further depth in Bandini et al.[18] The criteria for inclusion were: older than 18 years of age; grade A to D American Spinal Injury Association Impairment Scale (AIS); neurological level of injury between C3 and C8; impaired but not completely absent hand function. Exclusion criteria included the presence of another neuromusculoskeletal disease affecting the movement of the upper limb, upper limb joint deformity, and pain during the movement of the upper limbs. The participants were asked to record egocentric video using a head-mounted camera with a frame rate of 30 fps (Hero 5 Black, GoPro, San Mateo, USA). Participants recorded themselves performing naturalistic ADLs or instrumental ADLs over three 1.5-hour sessions over the course of 2 weeks in their own homes. A schedule for recording the daily activities was collaboratively developed between the investigators and participants, to ensure that the recordings were reflective of their real routines of ADLs while providing meaningful information for hand function analysis. More information about the data collection protocol can be found in Tsai et al.[27] The study was approved by the Research Ethics Board of the University Health Network (18-5225).

Clinical Assessment

Before the home recording period, the participants visited the rehabilitation center, where SCIM[28] and the GRASSP were collected. The SCIM evaluates functional independence following SCI by assigning a score to each of 9 mobility items, 4 respiration and sphincter management items, and 6 self-care items. The GRASSP consists of a sensory (SE) evaluation of the hand, a manual examination of upper extremity muscle strength, and a prehension test. The prehension test consists of prehension ability (PR-A) and prehension performance (PR-P). PR-A examines how a person with SCI performs cylindrical grasp, an example of power grasp, lateral key pinch, an example of intermediate grasp, and tip-to-tip pinch, an example of precision grasp. PR-P measures how an individual performs 6 functional tasks with predefined grasps, including (1) pouring water from a bottle, (2) opening jars, (3) picking up and turning a key, (4) transferring 9 pegs from one board to another, (5) picking up 4 coins and placing them in a slot, and (6) screwing 4 nuts onto bolts. The GRASSP's Strength (ST)

Table 1. Demographic of the Participants in the Study.

ID	Sex	Age	MFI	T/NT	LI	AIS	DH	UEMS	SCIM-TO	SCIM-SC	G-ST	G-PR-A	G-PR-P	G-SE
1	M	46	57	T	C4	B	R(L)	14	30	1	22	1	13	21
2	M	61	60	T	C4[a]	D[a]	L(L)	48	100	20	97	24	60	39
3	M	54	53	T	C4[a]	D[a]	L(R)	42	83	8	79	17	32	21
4	M	53	12	NT	C6	D[a]	R(R)	45	98	20	91	23	57	37
5	M	44	25	T	C5[a]	D[a]	R(R)	48	100	20	98	24	60	46
6	M	63	51	NT	C4[a]	D[a]	R(R)	43	89	20	86	24	58	31
7	M	47	88	T	C8	D[a]	L(L)	46	99	20	93	24	60	34
8	M	63	18	T	C5	D[a]	R(R)	28	87	8	43	7	24	42
9	M	63	91	T	C4	[a]	R(L)	30	26	3	53	9	21	5
10	M	61	13	T	C3[a]	C[a]	R(L)	39	81	16	74	19	39	27
11	M	49	240	T	C5	C	L(L)	17	37	6	31	4	13	19
12	M	63	13	T	C5	D	L(L)	49	100	20	98	24	57	39
13	M	54	31	T	C3	C	R(R)	28	25	1	47	18	17	13
14	F	62	38	T	C4	D	R(R)	37	52	6	76	21	54	44
15	F	21	17	NT	C5	D	R(R)	48	98	18	98	24	60	46
16	F	32	63	T	C7	D	R(L)	42	99	19	76	19	53	47
17	M	59	15	T	C4[a]	D[a]	R(R)	44	96	18	90	24	53	26
18	M	63	432	T	C5[a]	B	R(L)	19	30	3	28	6	9	17
19	F	32	63	T	C7	D	L(R)	42	49	10	45	10	34	47
20	F	75	19	T	C5	D	R(L)	39	77	13	79	21	39	24
21	F	67	49	NT	C4	D	R(R)	47	100	20	94	24	58	37

Abbreviations: MFI, time from injury in months; T, traumatic; NT, Non-traumatic; LI, ISNCSCI level of injury; AIS, ASIA Impairment Scale grade; DH, dominant hand; UEMS, upper extremity motor score of the dominant hand post-injury (out of 25).
G-, SCIM-TO SCIM-SC refers to GRASSP, SCIM total, and SCIM self care, respectively. Age is in years.
Participants highlighted in gray were excluded from the study due to insufficient recorded hand-object interactions.
[a]Indicates self-reported information.

component scores 10 arm and hand muscles on each side using the 6-point Medical Research Council scale. GRASSP was also employed to extract the upper extremity motor score (UEMS) component of the International Standards for the Neurological Classification of SCI.[29] The demographic information of each participant is shown in Table 1. One participant, number 4, was recruited in the study but did not complete the study. Two more participants (1 and 19) were also removed from the analysis due to insufficient hand-object interactions collected during daily activities ($<$.05 quantile of the data distribution).

Annotation

A grasp is a static hand posture used to firmly grasp or handle an item. We followed an established hand taxonomy developed previously with the 3 main hand grasp categories: power, precision, and intermediate grasp.[30] We also added a non-prehensile category to obtain a comprehensive taxonomy.[31] In a power grasp, the arm drives object movement, and pressure is created between the palm and somewhat flexed phalanges. In this spirit, any type of hand grasp in which the perceived force exerted between the hand and an object is perpendicular to the palm is referred to as a power grasp. In a precision grasp, the hand moves intrinsically without moving the arm, and pressure is applied between the distal phalanges. To minimize potential ambiguities resulting from limited visibility within a given frame and the absence of force data in cases where the force is parallel to the palm, we distinguished a precision grasp as one that engages the distal and intermediate phalanges and a power grasp as one that employs the palm and proximal phalanges to exert forces.[11] In an intermediate grasp, both power and precision grasps are present in nearly the same proportion, and an intermediate phalanx exerts pressure. There is no net force in any of the grasps examined thus far. However, in a non-prehensile grasp, the net force between the hand and the object is not zero. Pushing, sliding, rolling an object, and carrying items on a tray are examples of non-prehensile grasps.[32,33] We also considered non-prehensile grasps when bimanual tasks were performed using non-prehensile grasps, such as exerting pressure on each other to move a bottle.

Figure 1 depicts an example for each grasp.

The recorded videos were reviewed for each participant, and the hand-object interactions were selected from videos recorded for the right and left hand. In order to reduce the effect of repeated actions on the prevalence of the grasp

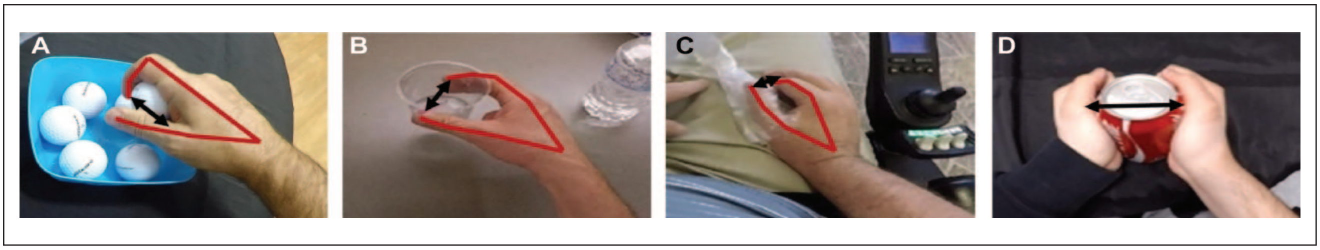

Figure 1. Four grasp types considered in this study. (A) Power. (B) Precision. (C) Intermediate. (D) Non-prehensile.

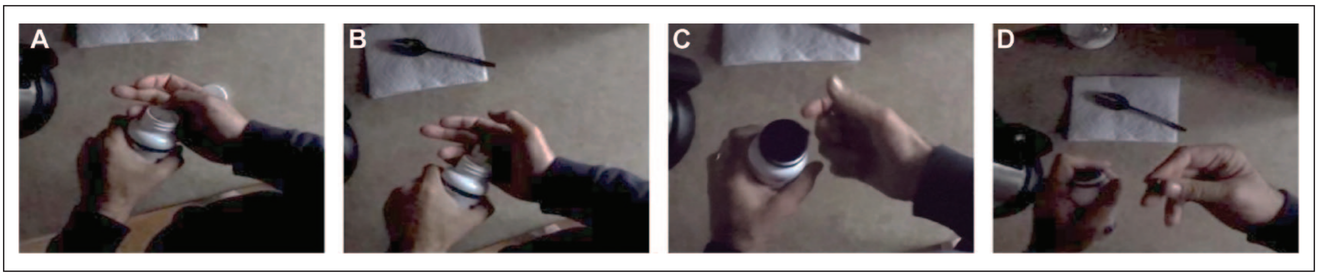

Figure 2. Right hand grasp from transitory grasp to stable. (A) Unknown. (B) Non-prehensile. (C) Power. (D) Precision grasp.

types, we only included the first interactions if consecutive interactions using exactly the same grasps were performed. Each activity was annotated as 1 of 5 grasp categories: power, precision, intermediate, non-prehensile grasp, and unknown grasp. An unknown grasp was defined as one that was not captured by a previously developed hand taxonomy.[30] Unknown grasps and frames in which a person applied multiple grasps simultaneously to manipulate an object were excluded from the analyses. In total, 716 grasps were excluded from the further analysis. We annotated 4432 interactions (760 955 frames) of which 2431 and 2001 interactions were performed with the right hand and the left hand, respectively. All annotations were performed by a single individual (MD), and the entire annotation process was carried out twice as a verification step to reduce mislabeling. To verify the accuracy of the annotations, 473 video frames that represented all types of grasps were labeled by a second annotator. After evaluating the inter-annotator agreement using Cohen's Kappa score (CKS),[34] we found a high level of agreement between the annotations (CKS = .81).

Manipulating an object necessitates the practice of several grasps in transitory and stable stages.[35] Figure 2 depicts a participant using unknown and non-prehensile grasps during the transitory phase and precision grasp in the stable phase. To reduce the complexity of the analysis, only the stable portion of the grasp was used to annotate the grasp type.

Statistical Analysis

The proportions of each grasp type employed by each participant in the annotations were computed, as well as the duration (in frames) of each grasp use instance. The relationships between the clinical scores and the proportion of grasp use and the mean average of grasp duration were examined using Spearman correlation. Statistical significance was set to $\alpha = .05$. The mean average of grasp duration for the 4 grasp groups were compared using a Kruskal–Wallis test, followed by Dunn's test for *post hoc* pairwise comparisons with Bonferroni correction, to determine if certain grasp types were associated with longer interactions.

Results

Grasp Use

The proportion of 4 grasp types used by individuals with cervical SCI for various daily activities was investigated. Figure 3 shows the percentage of each grasp employed by each participant. On average, the participants use power grasp to perform 34% ± 13% of their object interactions, precision grasp in 27% ± 15%, intermediate grasp in 13% ± 7%, and non-prehensile grasp in 26% ± 22%.

We also measured the mean time needed to perform each grasp type. The average time for power grasps was 13.1 ± 6.8 seconds, 6.5 ± 4.5 seconds for precision grasps, 8.0 ± 12.1 seconds for intermediate grasps, and 6.7 ± 10.6 seconds for non-prehensile grasps. The detailed results for each participant are shown in Figure 4. As different individuals may use each grasp a different number of times, we measured the mean duration of all instances occurring for each grasp type. Significant differences were

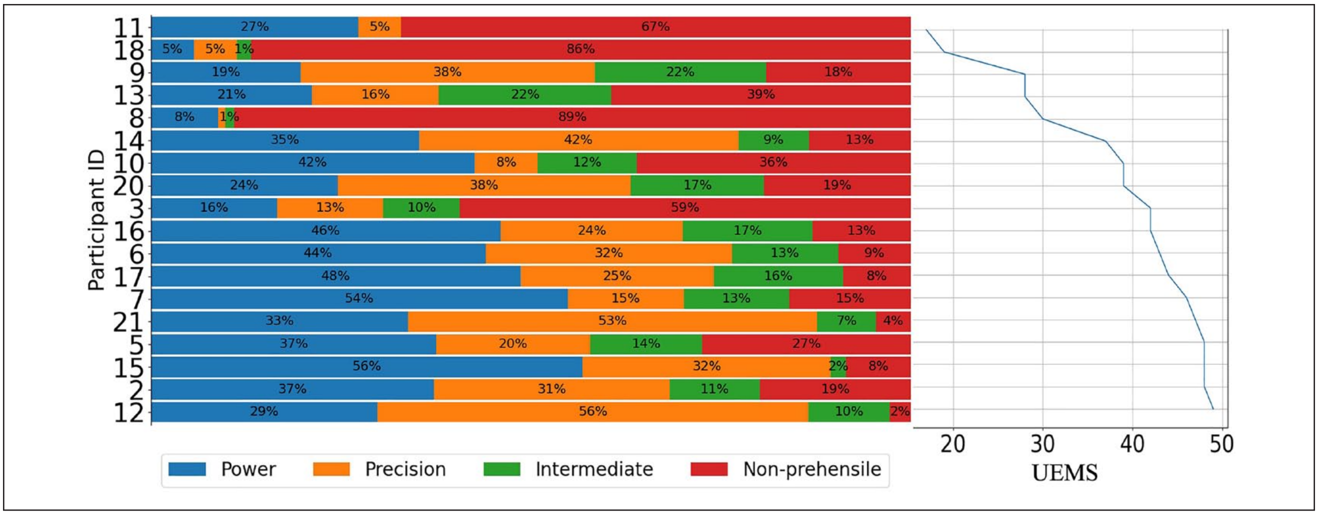

Figure 3. The proportion of grasp type use per study participant. The participants are sorted from top to bottom based on increasing bilateral UEMS.

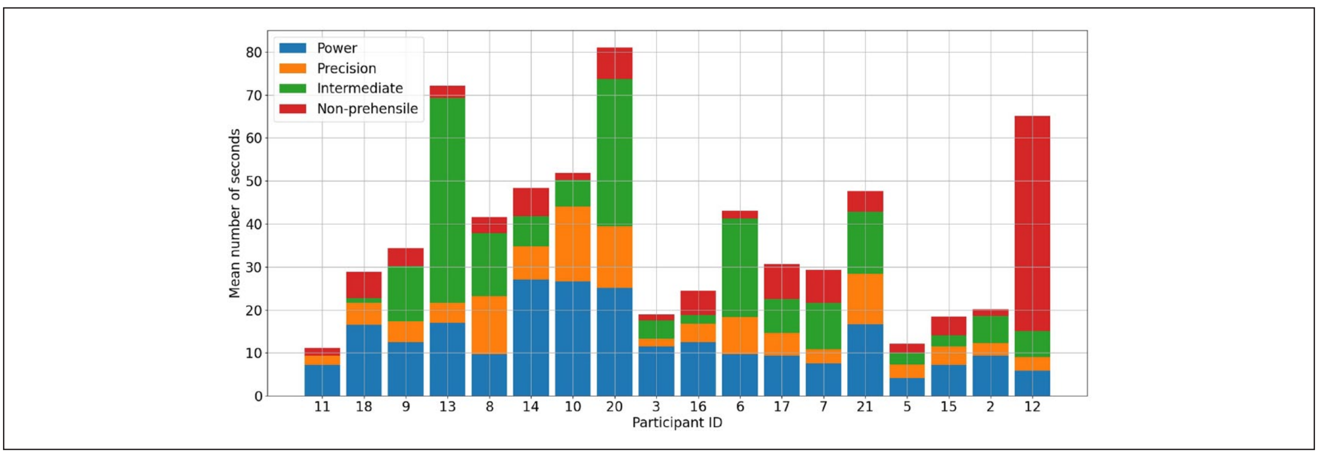

Figure 4. Average number of seconds to perform a grasp. The participants are sorted based on increasing bilateral UEMS.

found between the durations of the different grasp types ($P = .001$ for the mean duration using Kruskal–Wallis tests). We conducted *post hoc* Dunn's tests to identify the significant differences between grasps. The results demonstrate that the durations of power grasps were significantly greater than precision ($P = .02$) and non-prehensile grasps ($P < .001$).

Relation With Clinical Score

Using Spearman's correlation, we determined the association between grasp proportion and duration and the SCIM, GRASSP, and UEMS scores. The results are shown in Table 2. The frequency of employing power grasp, particularly, had strong positive correlations with SCIM Self-Care, UEMS, GRASSP PR-A, GRASSP PR-P, and GRASSP ST, and moderate positive correlations with SCIM Total and GRASSP SE-D. The proportion of non-prehensile grasp use had strong negative correlations with UEMS, GRASSP PR-A, GRASSP PR-P, and GRASSP ST, and moderate negative correlations with SCIM Total and SCIM Self-Care. Precision grasp also had a strong positive correlation to GRASSP PR-A and moderate positive correlations to UEMS, GRASSP PR-P, and GRASSP ST. We found moderate negative correlations between the mean power grasp duration and SCIM total, SCIM self-care, UEMS, and GRASSP-ST.

Discussion

This study investigated how people with cervical SCI use their hands to engage with their environment at home using

Table 2. Correlation Between the Proportion of Use and Mean Duration of Power, Precision, Intermediate (Intmed), Non-prehensile (N-prehen) Grasps and Bilateral Clinical Scores, SCIM-total (SCIM-TO), SCIM-Self-Care (SCIM-SC), UEMS, GRASSP PR-A (G-PR-A), GRASSP PR-P (G-PR-P), and GRASSP SE (G-SE).

	Grasp/Corr	SCIM-TO	SCIM-SC	UEMS	G-PR-A	G-PR-P	G-ST	G-SE
Proportion	Power	**0.54***	**0.64****	**0.61****	**0.69****	**0.75****	**0.60****	**0.48***
	Precision	0.31	0.34	**0.48***	**0.63****	**0.47***	**0.57***	0.22
	Intermed	−0.08	0.04	0.06	0.23	0.06	0.10	−0.23
	N-prehen	**−0.54***	**−0.59****	**−0.66****	**−0.78****	**−0.64****	**−0.69****	−0.37
Duration	Power	**−0.54***	**−0.50***	**−0.51***	−0.44	−0.41	**−0.51***	−0.27
	Precision	−0.24	−0.14	−0.27	−0.20	−0.17	−0.22	−0.11
	Intermed	−0.15	−0.01	−0.06	0.17	0.02	−0.01	−0.24
	N-prehen	0.13	0.11	0.16	0.28	0.12	0.18	0.11

*$P < .05$. **$P < .01$. Bold values indicate statistically significant results.

4 main grasp types. The types of grasps and the proportion in which they are used are influenced by environmental factors such as object shape, size, weight, the purpose of the grasps, the variety of activities, and physical constraints such as hand immobility. For example, cleaning and tidying tasks do not require dexterous hand movement, which results in using more power grasps.[26] Previous research demonstrated that the level of hand impairment in hemiplegic individuals reduces the number of viable grasp types, increases intra- and inter-individual variability of grasp movements, and influences the final grasp decision.[36,37] In this study, after annotating different activities from video data, we obtained a significant correlation with current gold-standard clinical assessments, demonstrating that the choice of grasp type, regardless of the environmental constraints, depends heavily on the impairment. Remarkably, the greater the impairment to the hand, the greater the reliance on non-prehensile grasping as a compensatory strategy, as highlighted by the negative correlations between the proportion of non-prehensile grasp use and UEMS, GRASSP, and SCIM subscores.

This research has the potential to elucidate new links between clinically-measured capacity and real-world performance. Particularly, we showed that the proportions of hand grasp use in the home environment strongly correlate with the majority of clinical scores, emphasizing the critical necessity of further understanding how grasp analysis in the naturalistic environment can contribute to measuring recovery after cervical SCI. Below, we will discuss the relationship between the grasp frequency with the clinical scores examined in the study:

1- SCIM, a clinical measure used to describe the ability to independently perform ADLs, correlates well with upper extremity assessments.[38] However, it is unable to give an exact insight into sensorimotor function, resulting in a lack of precision in describing to what extent the motor level recovery translates into an improvement of functional independence.[39] In this study, we provided evidence that reliance on power grasp is a crucial element reflecting self-care and independence, whereas relying on a non-prehensile grasp is suggestive of less independence.

2- GRASSP PR-A measures the capacity to practice power, precision, and intermediate grasp. We observed that having the ability to perform power and precision grasp results in using those grasps more often in the home environment. Those with less ability to use a power and precision grasp relied more on a non-prehensile grasp. The magnitude of the correlation between non-prehensile grasp use and GRASSP PR-A reflects the importance of including this category in grasp analysis after SCI. We also did not find any relationship between intermediate grasp use at home and GRASSP PR-A. This result may suggest that the capacity to perform various grasp types may translate to the free-life context to different degrees.

3- GRASSP PR-P quantifies the capacity to carry out predefined tasks. This score was positively correlated with the proportion of using power and precision grasp and negatively correlated with reliance on non-prehensile grasp in the home environment. The findings indicate that grasp analysis may play an important role in developing assessments that are more consistent across clinical and real-world environments than measures focusing on the amount of upper limb use.

4- GRASSP ST had a strong positive correlation with the proportion of using power and precision grasp but had a negative correlation with non-prehensile grasp. This finding was anticipated due to the fact that people with low GRASSP ST may not have the strength to execute a power grasp and instead depend mostly on non-prehensile grasp in order to carry out a manipulation. Increasing muscle strength results in an increased practice of power grasp and greater comfort with the usage of precision grasp in practical situations.

In our dataset, the power grasp was the most used on average, while the intermediate grasp was the least used. This result is corroborated by previous results that quantified the hand use of non-impaired individuals performing ADLs.[26] This result is expected because most ADL activities, such as cleaning tasks, including vacuum cleaning or scrubbing with towels, require the tool to be fixed to the arm and dexterous hand motion is not needed.[26] We also found a relation between practicing certain grasp types and the duration of a hand-object interaction. We showed that more time was spent on power grasps compared to precision and intermediate tasks. We also examined the relationship between interaction durations per grasp type and clinical scores. We found an inverse relationship between the mean duration of a power grasp and the scores obtained on the SCIM, UEMS, and GRASSP strength. According to these findings, people with milder hand impairment are able to perform power grasp tasks more quickly than those with more severe impairments. We found no connection between the duration of other grasp types (precision, intermediate, and non-prehensile grasp) and the clinical scores. Our findings are partially consistent with previous research that found no correlation between interaction time and clinical scores,[18] while indicating that a more detailed grasp analysis is necessary to understand the role of grasp duration.

A thorough hand assessment necessitates the examination of hand function using a variety of complementary metrics. Using egocentric video to analyze hand function at home provides the opportunity to extract several metrics that may otherwise be inaccessible. Hand evaluation in clinics only captures a subset of actual hand use in daily activities. Combining egocentric video with advanced machine learning algorithms[15-17,19] may allow analyzing other aspects of hand function, such as hand kinematics during reaching to grasping, or complexity of hand posture during transitory to stable grasp phases, to name but a few. These new metrics may be complementary to the information provided by a brief hand assessment in clinics. Practical methods for fine-grained evaluation have implications for tracking recovery after SCI and supporting the conduct of high-quality and efficient clinical trials.

Limitations and Future Work

This study used a wearable camera to record ADLs in people's homes. A recent study on the usability of wearable cameras in the rehabilitation context found that the camera's weight and heat constantly reminded participants that their activities were being recorded.[20] This awareness of video recording may cause a greater focus on performing a task that is not required for everyday activities, resulting in a biased hand measurement. Designing a new small camera for rehabilitation purposes is one possible solution. Nonetheless, egocentric video can directly capture the ADLs of individuals with SCI at home and provide detailed information on hand usage in a naturalistic environment that is unavailable during limited observation in clinics.

The majority of participants in this research had a low level of impairment, mostly AIS D, which could limit the generalizability of the results. Future work should include increasing the sample size to include more individuals with severe hand impairments. We speculate that the conclusions would remain consistent, because the current dataset had a large UEMS variance, indicating a high degree of variability in hand function. Having a larger sample size may also allow us to investigate the impact of hand dominance on the grasp use and frequency.

The research should be further expanded to examine the relationship between hand-grasping patterns and clinical scores in greater detail, emphasizing the need to use detailed hand taxonomies. However, employing a hand taxonomy developed for non-impaired individuals may not fully capture important variations observed with individuals with SCI, who may use hand grasping patterns not commonly observed in others. Developing a new data-driven hand taxonomy capable of encompassing a variety of injury severity levels and hand-grasping patterns is a potential solution to this problem.

Finally, we only evaluate hand functionality in a subset of video recordings when one of the 4 major grasps was employed during the steady period. It is possible that more insightful findings on hand function and the recovery profile could be obtained by analyzing hand movements from transitory to stable grasp phases, as well as expanding the analysis to include grasps not found in existing taxonomies, which were developed for unimpaired individuals. Nonetheless, the results provided here provide a strong demonstration that grasp analysis at home is highly relevant to assessing hand function after SCI, and to developing a better understanding of the links between capacity and performance.

Conclusion

In this study, we were able to show that the proportion in which different grasp types are used while conducting ADLs at home is an accurate reflection of hand function. This finding motivates additional research into the use of grasps in the home as a tool for better understanding and quantifying the recovery process after cervical SCI. The findings of this study may also permit the development of new wearable systems to monitor hand function recovery without the need for travel to clinics, for example in the context of telerehabilitation.

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Declaration of Conflicting Interests

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