Journal of Visualized Experiments

Capturing Representative Hand Use at Home Using Egocentric Video in Individuals with Upper Limb Impairment

--Manuscript Draft--

Article Type:	Invited Methods Article - JoVE Produced Video
Manuscript Number:	JoVE61898R1
Full Title:	Capturing Representative Hand Use at Home Using Egocentric Video in Individuals with Upper Limb Impairment
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Additional Information:	
Question	**Response**
Please indicate whether this article will be Standard Access or Open Access.	Standard Access (US$2,400)
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Please specify the section of the submitted manuscript.	Bioengineering
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TITLE:

Capturing representative hand use at home using egocentric video in individuals with upper limb impairment

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KEYWORDS:
Egocentric vision; Upper limb function; Outcome measures; Remote monitoring; Wearable technology; Hand function impairment; Hand function evaluation

SUMMARY:
A protocol is proposed to capture natural hand function of individuals with hand impairments during their daily routines using an egocentric camera. The goal of the protocol is to ensure that the recordings are representative of an individual's typical hand use during activities of daily living at home.

ABSTRACT:
Impaired hand function after neurological injuries can have a major impact on independence and quality of life. Most existing upper limb assessments are carried out in person, which is not always indicative of hand use in the community. Novel approaches to capture hand function in daily life are required to measure the true impact of rehabilitation interventions. Egocentric video combined with computer vision for automated analysis has been proposed to evaluate hand use at home. However, there are limitations to the duration of continuous recordings. We present a protocol designed to ensure that the videos obtained are representative of daily routines while respecting participant privacy.

A representative recording schedule is selected through a collaborative process between the researchers and participants, to ensure that the videos capture natural tasks and performance,

while being useful for hand assessment. Use of the equipment and procedures is demonstrated to the participants. A total of 3 h of video recordings are scheduled over two weeks. To reduce privacy concerns, participants have full control to start and stop recordings, and the opportunity to edit the videos before returning them to the research team. Reminders are provided, as well as help calls and home visits if necessary.

The protocol was tested with 9 stroke survivors and 14 individuals with cervical spinal cord injury. The videos obtained contained a variety of activities, such as meal preparation, dishwashing, and knitting. An average of 3.11 ± 0.98 h of video were obtained. The recording periods varied from 12-69 d, due to illness or unexpected events in some cases. Data was successfully obtained from twenty-two out of 23 participants, with 6 participants requiring assistance from the investigators during the home recording period. The protocol was effective for collecting videos that contained valuable information about hand function at home after neurological injuries.

INTRODUCTION:

Hand function is a determinant of independence and quality of life across clinical populations with upper limb impairments[1,2]. Capturing the hand function of individuals with hand impairments at home is vital to evaluating the progress of their ability to carry out activities of daily living (ADLs) during and after rehabilitation. Most clinical hand function assessments are conducted in a clinical or laboratory environment, rather than at home[3,4]. Existing clinical hand function assessments that seek to capture the impact on ADLs at home are questionnaires and rely on subjective self-reported ratings[5-7]. An objective evaluation to assess the ultimate impact of rehabilitation on hand function at home is still unavailable.

In recent years, many wearable technologies have been developed and implemented to capture upper limb function in real-world environments. Wearable sensors such as accelerometers and inertial measurement units (IMUs) have been commonly used to measure upper limb movements in daily life. However, these devices typically do not distinguish whether the detected epochs belong to functional upper limb movements[8,9], defined as purposeful movements intended to complete a desired task. For example, some wearable sensors are sensitive to the presence of upper limb swings during walking, which is not a functional movement of the upper limb. Furthermore, although wrist-worn accelerometers capture upper limb movements, they cannot capture the details of hand function in real-world environments. Sensorized gloves allow capturing more detailed information about hand manipulations[10], but they may be cumbersome for people whose hand function and sensation are already impaired. Wearable approaches have also been proposed to capture finger movements through magnetometry or finger-worn accelerometers[11-13], but the functional interpretation of those movements remains challenging[14]. Thus, although previously proposed wearable devices are small and convenient to use, they are insufficient to describe the details and functional context of hand use.

Wearable cameras have been proposed to fill these gaps and capture details of hand function during ADLs at home for neurorehabilitation applications[15-19]. Automated analysis of egocentric videos using computer vision has considerable potential to quantify hand function in context, by providing information both about the hands themselves and about the tasks carried out in real

ADLs[20]. On the other hand, the duration of continuous recordings is typically limited to approximately 1 to 1.5 h by battery, storage, and comfort considerations. Here, within these constraints, we present an egocentric video collection protocol intended to obtain data that is both representative of an individual's daily life as well as informative for hand function evaluation.

PROTOCOL:

The study was approved by the Research Ethics Board of the University Health Network. Signed informed consent was obtained from each participant before enrollment in the study. Signed informed consent was also obtained from any caregivers or household members appearing in video recordings.

1. Verification of the protocol applicability to the individual

NOTE: This protocol is intended to be applied to individuals with impaired but not completely absent hand function (specific criteria can be adapted to the population and/or question of interest).

1.1. Ask participants whether their affected hands impact their ability to carry out ADLs.

NOTE: It is recommended to ask participants to give some examples of tasks that they can and cannot perform independently with their affected hands.

1.2. Verify that the total score on the Montreal Cognitive Assessment (MoCA) is above 21, in order to avoid potential difficulties understanding and following protocol procedures.

2. Determination of the daily routine of participants

2.1. Ask participants to recall their daily routines over the past two weeks. Document which daily tasks are performed, for how long, and at approximately what time.

NOTE: The selected ADLs must be representative of each participant's typical activities, and be perceived by them as meaningful. Scheduling recording periods on different days is intended to increase the variety of recorded ADLs and to promote the capture of useful and meaningful data.

2.2. In collaboration with participants, select 3 timeslots of 1.5 h each during which to record videos. Select timeslots that are spread over different days of the week, and take place when ADLs involving the hands are typically carried out in sequence.

NOTE: Recording timeslots are scheduled for recording efficiency, but participants should understand that they have full control of when to start and to stop recordings.

3. Agreement on recording schedules and target video content with participants

3.1. Obtain agreement of each participant on the recording schedules, after discussing any concerns that they may have.

3.2. Set a goal of 3 h of videos over two weeks. Inform participants that insufficient videos may lead to extending their recording periods.

4. Emphasis of the importance of performing ADLs naturally

4.1. Instruct participants to focus on capturing realistic routines, instead of specifying particular activities to record. The intent of the instruction is to discourage participants from artificially recording specific activities in greater amounts than is typical for them.

5. Notification of potential privacy issues during recordings at home

5.1. Ensure that participants understand that all recordings should take place inside their homes, not in public places to avoid privacy issues.

5.2. Give some examples that may raise privacy concerns, such as bathing, dressing/undressing, and checking confidential information. Remind participants to be aware of mirrors, which may show their faces in the recordings.

5.3. Suggest that participants avoid the presence of other people such as family members or caregivers as much as possible in the videos.

NOTE: In the context of research studies, in cases where the presence of other people is unavoidable, informed consent should be obtained from those individuals.

6. Camera and tablet instruction

NOTE: If participants indicate during the initial contact that they require caregiver assistance for many of their daily needs, the caregiver is encouraged to also attend the study visit and be trained on the use of the equipment, so that they can later assist the participant.

6.1. Demonstrate how to use an egocentric camera (**Table of Materials**) to participants.

6.1.1. Demonstrate how to turn the camera on and off.

6.1.2. Demonstrate how to control recordings (start, pause, stop) using the camera.

6.2. Demonstrate how to use a tablet (**Table of Materials**) with the preinstalled camera app to control the recordings, if applicable.

NOTE: The demonstration includes controlling the recordings from the camera app, as well as replaying and editing (e.g., trim or delete) the recorded videos. A camera remote was initially considered (**Supplemental Files**), but in practice was not used because participants were comfortable using the camera or tablet to start and stop recordings.

6.2.1. Demonstrate how to turn on and off the tablet.

6.2.2. Demonstrate how to connect the tablet to the camera through the camera app.

6.2.3. Demonstrate how to control the recordings from the camera app.

6.2.4. Demonstrate how to review recorded videos from the camera app.

6.2.5. Demonstrate how to trim or delete the videos from the camera app.

6.3. Demonstrate how to don and doff the camera using an elastic headband adjustable to the participant's head.

NOTE: See **Figure 1**.

[Place **Figure 1** here]

6.3.1. Place the camera on the participant's forehead. Adjust the headband to wear the camera comfortably and steadily.

6.3.2. Ensure an optimal angle of the camera with respect to the forehead.

6.3.3. Ask participants to record a short segment of video while moving the hands in front of them and manipulating an object (e.g., the tablet).

6.3.4. Review the recorded video and ensure the two hands were clearly visible in the central region of the scene while conducting manipulation tasks.

6.3.5. Practice the use of the camera and tablet with participants and their caregivers, until they demonstrate proficiency.

7. Giving the equipment

7.1. Give the kit with all the equipment to participants to record their ADLs at home. In addition to the camera and tablet, the kit includes extra camera batteries, battery chargers for both camera and tablet, charging cables, headband for the camera, and a printed set of guidelines for using the camera (See the **Supplemental Material**).

8. **Experimental troubleshooting and followup**

8.1. Provide contact information of the researchers to help solve obstacles during the actual recordings at home. After one week, researchers call the participants to document the recording progress and solve any potential technical issues.

9. Retrieval of equipment and videos

9.1. Retreive all the equipment and videos from participants in person or through pre-paid mail parcels.

9.2. Ensure that participants agree to share all the videos returned. Participants are encouraged to review all of the collected videos before returning them to the research team, and to delete any portions that they do not wish to share.

9.3. For research studies, review the returned videos and check if anyone appears in the video without having given their consent. If so, send consent forms or call the individuals who appear in the videos to gain their consents for use of the videos. If the individuals are not reachable, the portions of the videos in which they appear are deleted by the researchers.

REPRESENTATIVE RESULTS:

Participant demographics and inclusion criteria

A sample of 23 participants was recruited for these studies: 9 stroke survivors (6 men, 3 women) and 14 individuals with cSCI (12 men, 2 women). Summary demographic and clinical information for the recruited sample are reported in **Table 1**.

[Place **Table 1** here]

The mutual inclusion criteria for both groups in these studies were: 1) over 18 years old, 2) impaired but not absent hand function, 3) absence of other neuromusculoskeletal disease affecting upper limb movements, 4) no deformity of upper limbs joints, and 5) absence of pain when moving upper limbs. Additional inclusion criteria for each of the two groups were as follows.

For individuals with cSCI: 1) neurological level of injury between C4 and C8 according the International Standards for the Neurological Classification of Spinal Cord Injury (ISNCSCI), 2) American Spinal Injury Association Impairment Scale (AIS) grade A-D. 3) Traumatic or non-traumatic injuries, 4) A unilateral ISNCSCI Upper Extremity Motor Score (UEMS) between 10 and 23 for at least one limb.

For individuals with stroke: 1) at least 6 months post-stroke, 2) total score on the Action Research Arm Test (ARAT) greater than 10, 3) Montreal Cognitive Assessment (MoCA) score above 21 to avoid potential difficulties understanding and following study procedures.

Content and length of recorded video

The videos used for the analysis presented here were from 22 of the 23 participants. The remaining participant (man with cSCI) returned the camera without any usable data after being out of touch with the research team for close to 6 months, and is not included in the remainder of the analysis. As such, the proposed protocol was successful for 95.7% of the participants. On average, participants recorded more than 5 activities. Activities included in the video recordings were meal preparation, eating, dishwashing, physical activity, and knitting (**Figure 2**). An average of 3.11 ± 0.98 h of video were obtained per participant, after discarding segments where other individuals were present who did not provide consent or where the data was not usable at all (e.g., camera was left recording on a table). In addition, the daily average video recording length per participant was 60 ± 33 min. Three participants postponed the recordings due to illness. Most participants recorded video following the agreed schedules, but they reported feeling tired and uncomfortable wearing the camera for over 1 h due to its weight and heat against the forehead. Additional recordings were scheduled to fulfill the 3 h video duration target when necessary. The average recording period required to acquire 3 hours of video was 22.3 ± 12.9 d. The recording periods ranged from 12 to 69 d, counting from the day the participant was given the camera to the day they returned it. In 4 instances, the length of videos obtained was lower than the 3 h target due to health conditions or scheduling constraints. Two participants took more than 2 months to record 2 h of videos due to family responsibilities. Another participant recorded nearly 2 h of videos over two weeks and then decided to return the camera because of travel plans. Another participant accidentally deleted all recorded video, and after being scheduled for additional recordings was able to provide only 1 h of video due to family responsibilities.

In addition to variations in duration, hand visibility influenced the quality of the videos. Some recorded activities did not show the hands clearly, such as physical training and reaching for objects in over-head cabinets. Hands were not shown in 3 ADLs from two participants with stroke. Regarding physical training, one participant was using an elastic band for upper limb exercises and playing tennis in the backyard. Hands in the video were not always visible since the arm movements were large and fast. Apart from the activities requiring upper limb movements with a wide range, most recorded ADLs were carried out within a workspace between the waist and shoulder, with the hands visible in the recordings. [Place **Figure 2** here]

Assistance required

Six out of twenty-two (27%) participants required assistance from the research team during the recording periods at home. On average, each help call took 5-10 min. No home visits were necessary. The difficulties encountered related to battery changing, Bluetooth connection, Wi-Fi connection, reviewing and trimming videos on the tablet, and controlling the recordings from the tablet. To solve these issues the following strategies were adopted:

As changing batteries may be difficult for individuals with impaired hand function, the researcher suggested to use the charging cable to recharge the camera. For technical issues related to camera-tablet connections (e.g., Wi-Fi and Bluetooth problems) as well as for reviewing videos on the tablet, the researchers verbally guided participants through the procedures step by step. For the issues related to trimming videos, assistance was provided when participants returned videos to the researchers in person to avoid unintentionally deleting other recorded videos. In case participants were not able to use the tablet to start and stop the recordings, they were told to use the camera alone, by clicking the recording button to control the start and stop of the video recordings.

Privacy concerns

Consistent with previous findings[21], most participants and their family members did not report privacy concerns about recording ADLs at home. One family member of a participant was unwilling to be included in the video, and the participant was able to avoid the situation. In total, one participant was assisted with trimming the returned videos. Qualitative analyses of participants' views on the collection of egocentric videos at home will be reported elsewhere, however, privacy considerations did not result in any obstacles to the data collection in these studies. In this protocol, the ADLs were recorded in home environments in order to avoid privacy concerns in public spaces. Apart from the participants, 15 bystanders (including caregivers and family members) of participants were included in the returned videos and consented to their inclusions in the study. Among the 15 bystanders included in the videos, 6 of them were not identifiable since their faces were not shown. In addition, approximately 20 min of videos from 2 family members of participants with stroke were discarded because portions of the videos showed their faces without their consents.

FIGURE AND TABLE LEGENDS:

Figure 1. Wearable camera setup. (A) Positioning of the egocentric camera. **(B)** Viewing angle from the camera.

Figure 2. Examples of two frequently recorded ADLs from the videos obtained. (A) Meal preparation**. (B)** Dish washing.

Table 1. Demographic and clinical information of the recruited participants.

DISCUSSION:

We presented a protocol for recording videos of ADLs at home using wearable cameras in individuals with upper limb impairments, such as cSCI and stroke. The protocol is flexible and can be goal-directed to capture hand function performance in specific ADLs or to track the progress of rehabilitation remotely in people living at home. The egocentric vision paradigm has great potential for remote monitoring of hand function in individuals living in the community, and for optimizing rehabilitation once people are discharged from inpatient care. Despite some limitations related to comfort during extended use (e.g., over 1 h), egocentric cameras have considerable potential to capture the details of hand use during functional ADLs and to provide contextual information that cannot be obtained through accelerometers and IMUs. Potential applications of this technology include serving as the basis for new outcomes measures quantifying independent hand use at home, as well as analyzing postural information to identify grasping strategies or compensatory postures and inform therapy planning. Although wearable cameras allow us to capture natural hand use at home, the cameras cannot record continuously for several hours due to battery life, storage, and comfort limitations, though the rapid evolution of wearable technology may reduce these limitations in the near future. In order to capture representative routines of participants despite limited recording duration, the protocol presented here relies on a collaborative process between the researchers and participants to select an appropriate recording schedule.

Thanks to the data collected from individuals with cSCI and stroke survivors, we were able to refine the protocol and identify pitfalls and gaps that could be improved in future studies. For example, the recording period usually took longer than the anticipated two weeks to obtain 3 hours of video data. In our studies, these situations were usually caused by unexpected events (e.g., illnesses, unexpected travels out of town, etc.) which prevented participants from recording videos according the planned schedule. In these cases, we provided support to the participants via weekly phone calls, not only to check on the recording progress, but also to troubleshoot any technical issues that could arise from a non-frequent use of the technology. In total, 15 caregivers of participants were involved in helping to record videos at home. In addition to technical issues, there are two general recommendations to adopt when recording video data using wearable cameras in individuals with hand impairments: 1) Emphasizing *when* participants should record, rather than *what* they should record, in order to avoid recording artificially long durations of a single activity and increase the variety of ADLs. 2) Keeping the camera on for longer continuous recordings as long as it is comfortable to do so, in order to increase recording efficiency and capture naturalistic sequences of activities.

This protocol can be used to capture natural hand function in the context of a variety of activities. In the collected videos, some participants included not only necessities of daily living (i.e., eating) but also leisure activities. Giving participants the freedom to record activities of their daily routines, rather than specifying a strict list of ADLs, allowed us to achieve two important aims: first, we made sure that activities were conducted in a manner similar to the natural conditions; second, we were able to record a wide variety of activities. Nevertheless, participants were aware of the camera presence on their head and this feeling might have pushed some of them to record more activities than their normal routine.

To achieve efficient and meaningful video data collection in natural living conditions, we had to find a balance in the guidelines and information given to the participants prior to the video recordings. Giving too much direction about the most interesting activities to record might lead the participants to record only those activities, thus failing to capture their daily routines and performance of natural ADLs. On the other hand, not giving enough information might cause confusion in the participants, who might not record enough video or lose interest in the study. To solve these issues and find an optimal trade-off for successful data collection, a thorough training session with participants is essential, in order to understand their routines and to make sure they clearly understand the purpose of the study, which here focused on recording their natural routines rather than collecting a standard set of activities.

Three limitations of the proposed protocol can be identified. First, individuals with cognitive issues may have difficulty recalling their daily routines or learning how to use the equipment. Second, individuals with low hand function may require a caregiver to help with setting up the recordings at home. Third, since participants have the opportunity to trim or delete recordings, it is possible that they might remove examples of unsuccessful ADLs and bias the data obtained. Nonetheless, this possibility is made less likely by the fact that the recorded ADLs were regularly performed by the participants, and therefore they usually had established strategies to carry out the tasks successfully. Carefully communicating that the goal of using this protocol is to capture typical ADL performance and that variations in function are expected may decrease participants' desire to trim unsuccessful tasks.

Collecting videos of natural ADLs is essential for understanding the hand function of individuals with hand impairments at home. From the collected videos, researchers and clinicians are able to see the typical tasks performed at home, the use of the hands during these tasks, as well as the hand postures and compensation strategies that are adopted during object manipulations. The information obtained from videos is valuable in rehabilitation and allows for the development of innovative and intelligent tools for the automatic analysis of hand function at home. In fact, computer vision algorithms have been developed with the aim of quantifying hand usage (e.g., number and duration of hand-object interactions for each hand) in individuals with cSCI and stroke [16-18]. With the constant improvement of computer vision techniques for egocentric hand analysis and the availability of more collected video data, additional details regarding the quality of hand manipulations can also be obtained[20]. Eventually, the current protocol and the available technology will lead to a comprehensive description of hand use in individuals with upper limb impairments living in the community, with the end goal of optimizing their recovery and improving their quality of life.

ACKNOWLEDGMENTS:

The studies using this protocol were funded by the Heart and Stroke Foundation (G-18-0020952), the Craig H. Neilsen Foundation (542675), the Natural Sciences and Engineering Research Council of Canada (RGPIN-2014-05498), and Ministry of Research, Innovation and Science, Ontario (ER16-12-013).

DISCLOSURES:

The authors have nothing to disclose.

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Figure 1

(A)

(B)

Figure 2

(A)

(B)

	Age (years)	Duration after injury (months)
cSCI (N=14)	55.9 ± 7.1	56.4 ± 58.9
Stroke (N=9)	56.8 ± 19.3	94.4 ± 134.4

FMA-UE: Fu

Etiology	Level of Injury		Upper Limb Function Assessment (Mean ± SD)	
	Level of Injury	AIS	UEMS: Right Hand	UEMS: Left Hand
12 Traumatic 2 Non-traumatic	C4 – C8	A – D	18.1 ± 6.2	18.6 ± 6.4
5 Ischemic			FMA-UE: Affected Hand	ARAT: Affected Hand
4 Hemorrhagic			45.6 ± 17.3	37.1 ± 19.1

AIS: ASIA Impairment Scale; UEMS: Upper Extremity Motor Score
gl-Meyer Assessment for Upper Extremity; ARAT: Action Research Arm Test

Name of Material/ Equipment	Company	Catalog Number
Egocentric camera	GoPro Inc., CA, USA	GoPro Hero 4 and 5
Battery chager and batteries	GoPro Inc., CA, USA	MAX Dual Battery Charger + Battery
Camera charger	GoPro Inc., CA, USA	Supercharger
Camera frame	GoPro Inc., CA, USA	The Frame
Headband for the camera	GoPro Inc., CA, USA	Head Strap + QuickClip
SD card	SanDisk, CA, USA	32GB microSD
Tablet	ASUSTeK Computer Inc., Taiwan	ZenPad 8.0 Z380M

Comments/Description

A camera that records from a first-person angle.

Extra batteries for the camera and battery charger

This charger is connected to the camera directly without disassembling the camera frame.

The hinge of the camera frame can be used to adjust the angle of view of the camera.

The tablet is installed with the GoPro App in order to connect with the camera.

Dear Professors Basteris and Patton,

We wish to thank the editor and reviewer for their suggestions, which have enabled us to significantly improve our manuscript. Point-by-point responses to each comment are listed below. In addition, a copy of the manuscript with the revised portions highlighted in blue is attached to facilitate the review process.

Editorial comments:

Changes to be made by the Author(s):

1. Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues.

Thank you very much for carefully reading through the manuscript. We have carefully proof-read the manuscript for spelling and grammar.

2. Please remove the GoPro references from the supplementary file if possible. In the manuscript, it is referred to as a remote camera.

Thank you for the suggestion. The GoPro and ASUS are now referred to as “camera” and “tablet” in the supplementary document.

3. Please ensure that all text in the protocol section is written in the imperative tense as if telling someone how to do the technique (e.g., “Do this,” “Ensure that,” etc.). The actions should be described in the imperative tense in complete sentences wherever possible. Avoid usage of phrases such as “could be,” “should be,” and “would be” throughout the Protocol. Any text that cannot be written in the imperative tense may be added as a “Note.” However, notes should be concise and used sparingly. Please include all safety procedures and use of hoods, etc.

The protocol section was revised with imperative sentences. As for safety procedures, no other equipment was used for safety reasons. Participants were informed to take off the camera when they felt uncomfortable wearing it.

4. The Protocol should contain only action items that direct the reader to do something. Please move the discussion about the protocol to the Discussion.

Thank you for the recommendation, sections not providing direct protocol instructions have been moved to the Representative Results or Discussion sections, as appropriate.

5. The Protocol should be made up almost entirely of discrete steps without large paragraphs of text between sections. Please simplify the Protocol so that individual steps contain only 2-3 actions per step and a maximum of 4 sentences per step.

We have ensured that each step in the protocol contains 1-2 actions of length limited to three sentences.

6. Please add more details to your protocol steps. Please ensure you answer the "how" question, i.e., how is the step performed? Alternatively, add references to published material specifying how to perform the protocol action.

Thank you for the suggestions. The details of each step have been elaborated in the protocol.

7. Please highlight up to 3 pages of the Protocol (including headings and spacing) that identifies the essential steps of the protocol for the video, i.e., the steps that should be visualized to tell the most cohesive story of the Protocol. Remember that non-highlighted Protocol steps will remain in the manuscript, and therefore will still be available to the reader.

The essential steps have been highlighted in yellow in the protocol as suggested.

8. Please ensure that the highlighted steps form a cohesive narrative with a logical flow from one

highlighted step to the next. Please highlight complete sentences (not parts of sentences). Please ensure that the highlighted part of the step includes at least one action that is written in imperative tense.

Thank you for the suggestion. All the highlighted sentences contain at least one action.

Reviewers' comments:

Reviewer #1:

Manuscript Summary:

This paper reports on the methods of a egocentric video recording system for quantifying real world hand use in a small sample of adults with stroke and spinal cord injury. Participants were asked to wear a camera on their hand and record daily activities such as activities of daily living and instrumental activities of daily living. Participants were instructed on how to edit the video clips and properly wear the camera. Overall, it took 12-69 days to achieve 3 hours of video. While novel methods for recording real-world hand use after neurological injury are important, this system places a heavy burden on participants and may only apply to higher level patients. Please consider the comments below to help clarify these methods and address limitations of this system.

Major Concerns:

1. The egocentric video recording process took 12-69 days on average to achieve 3 hours of video data. That is a very long period of time for so few hours of real-world hand performance data. A major concern is the burden of this method on participants and the length of time required to achieve sufficient recordings. At 12 days, 3 hours of video is less than 1% of available hours. Does that really provide much information about real world hand use?

Thank you for your comments. The protocol is specifically designed to obtain video reflective of real-world hand use while using limited recording durations. In this way, the unique information provided by egocentric video can be acquired in an efficient manner. Key elements of the protocol put in place to achieve this goal are as follows. First, the recorded ADLs were selected in collaboration with the participants to capture representative aspects of their typical day to day life. The involvement of the participants in this process is a key aspect of the methodology. Second, they understood that the goal of this study was to capture natural hand function rather than record large amounts of hand activities, since this latter strategy tends to result in many artificial repetitions of a few activities. Third, the recording were scheduled at different timeslots across different days of the week in order to capture a variety of ADLs reflecting different aspects of participants' daily life. Based on these design choices, the 3 hours of video have considerable potential to represent daily hand use. While the choice of 3 hours is intended to balance practicality of data collection with information obtained, the benefits of having more video would not necessarily increase linearly with the recording time. For example, extended periods may not involve hand use (e.g. watching TV), while different meal times may reveal similar information. As such, the objective is capture representative data that provides insight into the individual's function, rather than to collect as many hours as possible.

Regarding the reported durations, we have now reported the average duration (22.3 ± 12.9 days, p.7 line 267-268), which helps to illustrate the presence of outliers in our dataset. Specifically, in some cases the recording period was extended for reasons related to on illness, family responsibility or travel plans, which were unexpected at the time of enrollment in this study. In these cases the long recording period was due to putting the recording schedules on hold rather than participants taking a long time to successfully record 3 hours.

2. Results: Thank you for listing the barriers to recording video and the reasons why participants were unable to meet the 3 hour video target. These are important when considering the feasibility of home based monitoring. With that, these issues call feasibility of this method into question. If participants do not like the camera because it is heavy and/or hot, or have difficulty finding time to record, etc. then this approach may be too involved for this population. While acceleromters and IMU devices lack specific information related to hand function, they are less invasive, easy to use, and provide far more data on upper limb movement. Please address these feasibility issues in the discussion or limitations section.

Thank you for your suggestion. We included the feasibility issues in the discussion section (p.8 line 336 - p.8 line 342 and p.9 line 386- p.10 line 395). Despite the comfort limitations of weight and heat, all but one of the individuals in our study provided usable data by following this protocol. We argue that the amount of data that they collected was sufficient to describe their hand use, as discussed in our response to the previous comment. As such, we have demonstrated the feasibility of the approach in these two populations.

Regarding the use of accelerometers and IMUs, while we agree that they are easier to use for long data collection, the information that they provide is qualitatively different. The data collected from them are unable to identify whether detected movements belong to *functional ADLs*, which are purposeful task-directed movements. The definition of a functional task has now been included in the introduction section (p2 line73-74). Wrist-worn accelerometers provide information about arm movements but not hand function. As such, we respectfully suggest that the statement that they "provide far more data on upper limb movement" must be qualified. They provide more data about arm movement, but far less data about the hand. Wearing accelerometers and IMUs directly on the hands may influence participants' hand movements, especially for participants with hand function impairments, and still fail to provide the functional context. The egocentric camera is better suited to capture hand function during functional ADLs without interfering with the natural hand movements of individuals with hand impairments.

In addition, given the constant improvement of computer vision approaches, we believe that a camera-based technology has a better chance to record hand function of people with hand impairments than accelerometers or IMUs, especially if the aim is capture natural hand-object interactions and activities without interference. Moreover, considering that lighter wearable cameras are currently under development for entertainment and augmented-reality purposes, some of the above issues related to the hardware could soon be solved by newer technologies.

3. There are other devices that quantify real-world hand function. This paper would benefit from mentioning these other devices and how the egocentric video system compares to other, smaller, less intrusive methods (e.g. manumeter- Friedman et al., 2014 and Rowe et al. 2013).

Thank you for your suggestion. We have now included the references related to the manometer as well as finger-worn accelerometry studies to the Introduction section (p.2 line 78-82). Devices worn on the fingers may in some cases affect function, and more importantly still only capture body movements but lack the functional context. These differences are now mentioned in the Introduction (p.2 line 73-75), to clarify the potential role of egocentric video.

4. While this is a methods paper, it would be helpful to know what the primary outcome variables would be from this method. Stated differently, how are the video clips analyzed when

the video recordings are returned? Do the authors examine quality of movement, displacement, accuracy, etc?

Thank you for your comment. The types of information that can be extracted was previously detailed in the last paragraph of the discussion (p.10 line 398-400), specifically, amount of functional hand use in each hand, as well as postural information that can reveal the choice of grasping strategies and the use of compensatory postures.

5. A major benefit of using accelerometers and IMU devices is that they can be worn by individuals with cognitive impairment and a wide range of upper limb impairment because they do not require anything from the participant except to wear the device on their wrist or finger. The video system places a larger burden on patients which will limit the number of people this method can be used for- mostly to those of higher functional status. Please consider mentioning this limitation in the discussion section.

Thank you for the comment. We have now added a limitations paragraph to the Discussion and acknowledged that the protocol is more appropriate to individuals without cognitive impairment (p.9 line 368-387). The protocol can be used with individuals who have lower levels of function, if a caregiver is available who can help with the equipment. This has also now been mentioned in the limitations. In our studies, one stroke survivor who had severe upper extremity impairment (according to the severity level from the Fugl-Meyer Assessment for Upper Extremity in Luft, A.R., et al. (2004)) participated with a caregiver's help. The participant with low hand function was able to participate with adequate assistance.

6. Methods- allowing participants to delete/edit video clips for privacy makes sense. However,

this does extend the option for participants to delete clips when they may have failed at an activity or clips of hand use that were sub-optimal to the participant. The result of this could be only video clips that participants felt their hand function was sufficient or of good quality. This would compromise the accuracy of real world hand use. Was this issue addressed during the training session? If not, it would be worth a discussion in the paper either as a limitation or in the methods.

Thank you for the feedback. The possibility of participants trimming videos to only include successful tasks was added to the Discussion section (p.9 line 389- p.10 line 395). In the training session, the goal of this study was explained to all participants and we reminded them not to perform extra activities beyond their daily routines. We also discussed with participants the importance of typical hand use in this study and asked them not to change the manner in which they typically performed the tasks. In addition, the tasks that they recorded were ones that they performed regularly, and which they therefore had strategies to carry out successfully. In our studies, only one participant requested to trim the recordings, and this was for privacy reasons rather than an unsuccessful task.

Reviewer #2:

Manuscript Summary:

This article presented a home-based study protocol using an egocentric camera to capture the hands of people with neurological injuries during usual activities of daily living.

Major Concerns:

Given the tennis example, will it be better to mount the camera in the work space rather than making it egocentric.

Thank you for your comment. We agree that mounted cameras in the home may capture larger areas in the frame, which may have benefits for activities containing wide range of motion. However, the hands may then be frequently out of view of the camera, especially when participants are far away or the hands are occluded from view. An egocentric camera is coupled with the head movements, such that the hands are typically visible in the videos, since a person usually looks at their hands and manipulated objects during a task. In addition, an egocentric camera enables recordings of ADLs across several rooms and environments. Therefore, in general, using an egocentric camera is much more suitable to record hand function during functional ADLs at home.

Minor Concerns:

0) Lin3 53: starting sentence with a digit. Also check rest of article

Thank you for reading through the manuscript carefully. We have ensured that sentences do not start with digits in the revised manuscript.

1) Line 75 -17 Why can't wrist-worn accelerometers captures details of hand function in the real world.

Thank you for the question. The reason why wrist-worn accelerometers cannot capture details of hand function is that they record *arm movements* rather than hand movements. Wrist-worn accelerometers are helpful to capture some aspects of upper limb function, but not hand function, which involves more degrees of freedom and fine movements that are largely decoupled from wrist movements.

2) How come the the swing not counted as a functional task of the upper limb.

Thank you for your comment. The definition of a functional task has been added to the Introduction section (p2 line73-74). A functional task in this study is defined as a purposeful movement intended to accomplish a specific action, such as grasping a glass *to drink* from it or cutting food *to make a meal*. By this definition, the arm swing is not part of functional ADLs. More generally, in situations where the goal is to track someone's ability to use their hands, tracking arm swings during walking is of limited interest.

3) Why is the time since injury for the SCI participants?

Thank you for this question, the duration after injury for participants with cSCI was included in Table 1. The time since injury for the participants with cSCI was 59.8 months (mean value) and ranged between 13 and 240 months. Since the time since injury was not a requirement for applying this protocol nor was it an inclusion criterion for our study with participants with cSCI, the information is included in Table 1 but not in the text.

4) What is the daily average video recording length?

Thanks for your advice. The daily average video recording length was added to the Representative Results section (p.6 line 263-264).

5) Line 216: I did not understand "12 to 69d". For what and who is this recording length referring to

Thank you for this question. The recording period, 12 to 69 days, is the range of durations for which participants kept the camera. This range covers all the participants, except for the one individual who did not return any useful data. The recording period for each individual was calculated from the day they brought the camera home to the day they returned it. This point has now been clarified in the manuscript.

July 30, 2020

Dear Drs. Jewhurst and Basteris,

We are pleased to have the opportunity to submit the enclosed manuscript entitled “Capturing representative hand use at home using egocentric video in individuals with upper limb impairment”. This submission is in response to your invitation to contribute an article to the collection “Rehabilitation Technology in the Real-Life Setting”.

The focus of our article is the use of egocentric video to capture hand function at home. Hand function is a key determinant of quality of life after neurological injuries, and egocentric video offers exciting new opportunities to capture hand function in context with an unprecedented level of detail. The protocol presented in our manuscript aims to ensure that the recordings are representative of an individual’s typical hand use during activities of daily living at home. We present representative results from studies on two different clinical populations with upper limb function impairments: individuals with cervical spinal cord injury and stroke. The studies of the two groups were approved by the Research Ethics Board of the University Health Network, Canada. The authors have no conflicts of interests to disclose, and we confirm that this manuscript is original and has not been submitted for review elsewhere.

I will be serving as the corresponding author for this manuscript. I have assumed responsibility for keeping my coauthors informed about the review process.

Sincerely,
Meng-Fen Tsai

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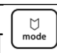
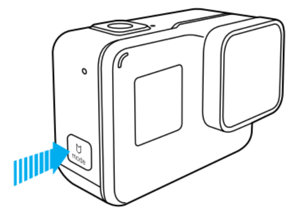
Egocentric Camera – Basic User guide

[INSERT CONTACT INFORMATION OF THE RESEARCH TEAM]

POWER ON / OFF

Press the Mode button for two seconds [

]



START / STOP RECORDING

Using the camera touch display:
Tap the icon in the lower left corner of the touch display

Using camera remote:

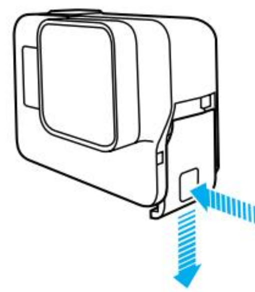
1. Pair camera Remote to camera (For most cases, this should already be paired out of the box):
   - From the main screen, swipe down from the top to bring up the menu and then select connect.
   - From the connect menu select “Connect New Device”
   - Now select the option “(Voice Remote)” A new message will appear on the camera screen asking you to power on the Remote. Set the camera aside.
2. Power on the remote by pressing hold the small power button on the side of the remote for 8 seconds.
3. From the main screen, swipe down from the top to bring up the menu and then select connect.

Using camera Apps:

Live preview, playback and full camera control (including start and stop recording) can be operated from the camera Apps.

CHARGING THE BATTERY

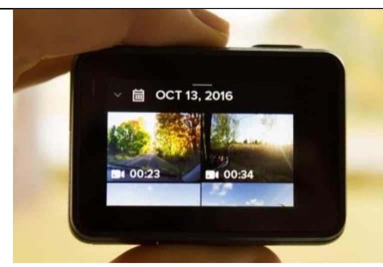
1. Hold down the Latch Release button on the side door (if available), then slide the door open.
2. Connect the camera to a computer or other USB charging adapter using the included USB-C cable.
3. Power off the camera. The camera status light turns on during charging and turns off when charging is complete. When charging with a computer, be sure that the computer is connected to a power source. If the camera status light does not turn on, use a different USB port.



VIEWING VIDEOS

Using the camera touch display:

1. Swipe right to open the gallery. If your microSD card contains a lot of content, it might take a minute for it to load.
2. Scroll through the thumbnails. Note: For photo series (Burst, Time Lapse, Night Lapse and Continuous photos), the thumbnail displays the first photo in the series.
3. Tap a video or photo to open it in full-screen view.
4. To add a HiLight Tag, tap [ ]. HiLight Tags make it easy to bookmarks videos for later retrieval.
5. To return to the thumbnails screen, tap [].
6. To exit the gallery, swipe down.



Using camera Apps:

Live preview, playback and full camera control can be operated from the camera Apps.

DELETE SELECTED VIDEO FILES

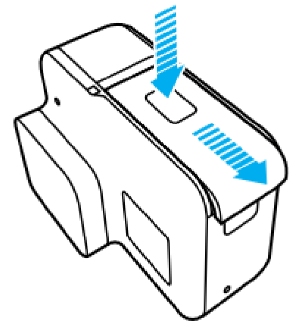
Using microSD card:

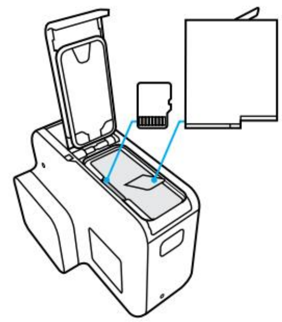
1. connect the card reader to the computer
2. Remove microSD card from the camera:

- Hold down the Latch Release button on the battery door, then slide the door open.
- To remove the card, press it into the slot with your fingernail and it will pop out.

3. **Insert** the microSD card into the microSD slot/reader on your computer or the tablet provided (via File Manager App):

- The microSD card slot (accepts up to 128GB capacity cards) on the tablet, can be found under the rear cover.





File Manager

4. Delete selected video files on your card

Using USB cable:

1. Connect the camera to your computer using the included USB-C cable
2. Power on the camera and follow the on-screen instructions
3. Delete selected video files on your card