Data logger technologies for manual wheelchairs: A scoping review

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Abstract

In recent years, studies have increasingly employed data logger technologies to record objective driving and physiological characteristics of manual wheelchair users. However, the technologies used offer significant differences in characteristics such as measured outcomes, ease of use and level of burden. In order to identify and describe the extent of published research activity that relies on data logger technologies for manual wheelchair users, we performed a scoping review of the scientific and grey literature. Five databases were searched: Medline, Compendex, CINAHL, EMBASE and Google Scholar. The 119 retained papers document a wide variety of logging devices and sensing technologies measuring a range of outcomes. The most commonly used technologies were accelerometers installed on the user (18.8%), odometers installed on the wheelchair (12.4%), accelerometers installed on the wheelchair (9.7%) and heart monitors (9.7%). Not surprisingly, the most reported outcomes were distance, mobility events, heart rate, speed/velocity, acceleration and driving time. With decreasing costs and technological improvements, data loggers are likely to have future widespread clinical (and even personal) use. Future research

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may be needed to assess the usefulness of different outcomes and to develop methods more appropriate to wheelchair users, in order to optimize the practicality of wheelchair data loggers.

Keywords

data loggers; wheelchair; manual wheelchair; scoping review

INTRODUCTION

Wheelchairs are frequently prescribed in the world of rehabilitation to facilitate independent mobility and promote social participation of individuals with mobility limitations. Manual and powered wheelchairs are used by nearly 240,000 Canadians (Smith, Giesbrecht, Mortenson, & Miller, 2016) and nearly 3.3 million Americans (LaPlante & Kaye, 2010). For many of these users, the wheelchair becomes an extension of their physical self, enabling various daily activities at home, work, or in the community, as well as the ability to fulfill different social roles. It is not surprising that, for many, the wheelchair represents a major factor of community reintegration (National Council on Disability, 1993; Noreau & Fougereyrollas, 2000; Scherer & Cushman, 2001), yet relatively little is known about the direct impact wheelchairs have on a user's daily activities and participation. Rousseau-Harrison et al. (2009) have found a positive link between wheelchair acquisition and social participation from a sample of individuals who presented a variety of diagnoses. Other studies also revealed the benefits of wheelchair use on quality of life (Davies, De Souza, & Frank, 2003; Devitt, Chau, & Jutai, 2004). However, some studies have documented the obstacles faced by wheelchair users, such as interpersonal and environmental barriers (Hoenig, Landerman, Shipp, & George, 2003; Meyers, Anderson, Miller, Shipp, & Hoenig, 2002). In order to understand the use and impact of wheelchairs it is important, from a clinical point of view and for researchers, to document the mobility characteristics of wheelchair users in the community and to obtain an accurate account of their activity levels (e.g. wheelchair propulsion, distance traveled, pressure-relief activities, etc.). For clinicians, this data may reveal information about how much the wheelchair is actually used and whether it helps fulfill the objectives identified with specific clients, or if changes are required. Unfortunately, it is difficult to obtain quantitative and accurate data. Much previous research has used subjective assessments, such as questionnaires, to document wheelchair-related activities; such techniques have inherent problems (Sallis & Saelens, 2000; Warms, 2006). In recent years, however, studies have increasingly employed electronic monitoring technologies to record objective driving and physiological characteristics of manual wheelchair users. Herein we will use the term "data logger" to refer to electronic devices that record information related to a wheelchair user's behaviour using one or more sensors and a data storage system. Data loggers may be fixed on the wheelchair or to the wheelchair user. Data logging devices have the potential to provide quantitative information about a multitude of mobility or physiological variables of wheelchair use. For example, data loggers can provide quantitative information regarding wheelchair propulsion (Postma et al., 2005; Washburn & Copay, 1999), daily "bouts of mobility" (Sonnenblum, Sprigle, & Lopez, 2012), as well as physical activity by measuring distance and speed traveled (Fitzgerald et al., 2003; Tolerico et al., 2007).

Of the data logging work that has been performed, the technologies used offer marked differences in characteristics such as measured outcomes, ease of use, burden, etc. This diversity in the literature may be confusing to therapists and researchers, as well as make it difficult for others to implement for their own studies or clinical use. This study was performed in order to obtain an overview of what has been done until now to quantify and objectively assess manual wheelchair use and physiological characteristics of the wheelchair users. Therefore, we have conducted a scoping review with the purpose of identifying the range of data loggers found in the scientific and grey literature and describing: 1) their underlying sensing technologies and 2) the outcomes they measure.

In this paper, the terms “logging devices” or “systems” refer to the data logger in its entirety. The terms “sensors” or “sensing technologies” refer to individual components of the data logger which detect physical quantities. These quantities may be outcomes themselves, or they may be subjected to further signal processing to obtain outcomes.

METHODS

We undertook a scoping review of the scientific and grey literature to examine the extent of research activity related to data loggers for manual wheelchair users. Because the literature corresponding to this goal is broad and emerging, it was more appropriate to conduct a scoping review rather than a systematic review (Arksey & O'Malley, 2005; Levac, Colquhoun, & O'Brien, 2010). This method allows for the incorporation of a broad range of study designs from both the published and grey literature (Levac et al., 2010). Moreover, our goal was not to answer a specific research question but rather to map the available literature (i.e. its nature and extent) within a specific research area, which is an important distinction that is commonly used to define a scoping review (Grant & Booth, 2009; Levac et al., 2010). In order to ensure a rigorous and well-designed protocol we adapted the methodology described by Arksey and O'Malley (2005) and Levac et al. (2010). Since this type of review is relatively new, we also used relevant components of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Moher, Liberati, Tetzlaff, Altman, & PRISMA Group, 2009), as proposed by Pham et al. (2014), to address the lack of a consensus on methodological procedures about reporting guidelines for scoping reviews (Brien, Lorenzetti, Lewis, Kennedy, & Ghali, 2010).

Literature Search

A flowchart describing our search and review method was established (Figure 1). A co-author (JL) searched four databases: Medline (source: PubMed), Compendex, CINAHL and EMBASE, using these specific keywords: (data log* OR monitor* system OR log* system OR activity log* OR activity monitor* OR mobility log* OR mobility monitor* OR monitor* device OR “cycle computer” OR “cyclometer”) AND (wheelchair*). We limited our search to publication dates between January 1979 and November 2014. Because Google Scholar does not recognize the truncation symbol (*) and uses automatic stemming, we searched it using a combination of keywords similar but not identical to the one used for the databases: (“data logger” OR “monitoring system” OR “logging system” OR “activity logger” OR “activity monitoring” OR “mobility logging” OR “mobility monitoring” OR

“monitoring device” OR “cyclometer” OR “cycle computer”) AND (“wheelchair” OR “wheelchairs”). We included Google Scholar among the search engines despite its lack of curation because it provides a broad search across the “grey literature”: not just articles from peer reviewed journals but also publications such as theses and conference proceedings. Finally, since the initial search in the databases was conducted in November 2014, we did an update. We repeated the search on the same search engines using the same combinations of keywords on June 10, 2015 (Figure 1).

Study Selection

To start the selection process, citations from the four databases were exported to EndNote, where we applied the “Find Duplicates” option. A manual check of the citations was performed to find other duplicates which were not noticed by the software. A search in Google Scholar was then performed, and duplicates were noted and discarded. The research assistant then reviewed all of the publication titles and/or abstracts and discarded those that were clearly irrelevant. Remaining articles were read in greater detail to assess their eligibility according to the criteria described below. When questions about inclusion/exclusion criteria or details of certain technologies were raised, the other co-authors provided feedback on the process of study selection. A paper was removed if it was a research review article, if it was not related in any way to wheelchairs or wheelchair users, if an abstract and/or text was not available, or if it was written in a language other than English or French. Furthermore, we excluded papers that presented or used logging devices that were not suitable for wheelchairs and/or not mentioned to be so, were not fully described, were not suitable for use in the community, were only used for comparison and/or were not intended to sense and store data. Any paper that: 1) met the above criteria, 2) presented the development or the use of a data logger that can be employed with manual wheelchairs, and 3) presented the mobility or physiological outcomes that the data logger and its sensing technologies can measure, were included.

Data Extraction

After publications relevant to the scoping review were identified, the research assistant, with the help of one author (FR), identified/described the following for each study: 1) if it was a developmental study (e.g. describing and validating data logger technology development for wheelchair use) or a study which used data logger devices to answer a research question, regardless of the design employed (hereafter to be referred to as an “experimental study”); 2) a brief description of the data logging device; 3) the way the device was powered, and its reported battery life; 4) the measured outcomes, for instance measures of mobility (e.g. speed, distance, etc.) or physiology (e.g. heart rate, VO_2 , energy expenditure, etc.); 5) the sensing equipment/technology (e.g. accelerometer, gyroscope, compass, GPS); and 6) if the system was fixed on the wheelchair or to the wheelchair user. All data were recorded in a table developed for this study. For validation, a second research assistant (a rehabilitation engineering research technician) reviewed all of the data extracted. Any discrepancies were resolved via discussions, and any necessary adjustments were made to the table.

Data Analysis

We used descriptive quantitative analysis to investigate the extracted data. Specifically, we calculated the frequency with which studies used each sensing technology and measured each outcome. In some cases, sensing technologies or outcomes were grouped into categories. For example, odometers were grouped together regardless of whether they were mechanical, optical or magnetic, and outcomes related to speed and velocity were grouped together.

RESULTS

The scoping review search strategy identified 6,087 papers (once duplicates were eliminated). After the initial screening of titles and/or abstracts, 208 papers remained according to our exclusion/inclusion criteria. Of those articles, 104 papers specifically related to manual wheelchairs were kept for analysis (Figure 1). The update conducted in June 2015 identified 15 additional papers. Therefore, a total of 119 papers were included in this scoping review (Figure 1). Although we wanted to examine the extent of research activity that focused on data logger technologies for manual wheelchairs, we included some studies (n=18) that presented a system used with both manual and powered wheelchairs. Note that three different situations occasionally occurred that impacted the reporting of the number of loggers and technologies included in the analysis: a paper may have described more than one logger, one logger was often used in more than one paper, and one logger often includes more than one sensor technology. All of the extracted data for each retained paper were compiled in a table (available as a supplementary file, including the references of the 119 retained papers). However, most of the significant data from this supplementary file, except the detailed description of the logger devices, are summarized below, especially in Tables 1, 2, 3, and 4.

Description of the Studies

Most of the selected papers for this scoping review were recent: 69.7% of them were published between 2010 and 2015 (Table 1). For each paper, we identified if it was a developmental study, in which the authors described a system's development, components, and/or functioning as well as the outcomes/variables it was designed to measure; or if it was an experimental study, in which the authors presented an experiment where a data logging device was used to answer a specific research question. Of the retained papers, 50.4% (n=60) were developmental, 42.9% (n=51) were experimental, and 6.7% (n=8) were both developmental and experimental.

Data Related to Logging Devices, Sensing Technologies and Measured Outcomes

Table 2 presents the frequency with which each sensing technology was reported in the selected papers. Regarding all of these technologies (n=217), 50.7% (n=110) were installed on the wheelchair and 49.3% (n=107) were fixed to the wheelchair user. The most commonly used technologies were accelerometers fixed to the user (n=41; 18.8%), odometers installed on the wheelchair (n=27; 12.4%), accelerometers installed on the wheelchair (n=21; 9.7%) and heart monitors (n=21; 9.7%). Table 3 presents the frequencies at which each outcome was measured by the logging devices presented in the selected

papers: the number of papers reporting the outcome, the total number of times the outcome was measured (n=433) and the percentage of the total number of measured outcomes it represents. The most reported outcomes were distance (n=47; 10.9%), mobility events (n=45; 10.4%), heart rate (n=42; 9.7%), speed/velocity (n=39; 9.0%), acceleration (n=35; 8.1%) and driving time (n=27; 6.2%). Table 4 specifies whether these outcomes were obtained by sensing technologies installed on the wheelchair, on the user, or on the wheelchair and the user. Table 5 provides a definition of each outcome that represents at least 2.0% of the total outcomes.

A total of n=91 different logging systems were described in the selected papers. Of those, information about the power source and battery life was provided for 35.2% (n=32). However, for some systems (n=13; 14.3%) whose battery life was not clearly specified, details concerning the duration that they were operating during the experiment were presented, and we have assumed in those cases that they were not recharged during that period.

Two data logging systems were used in a relatively large number of papers: 1) a custom data logger (magnetic odometer) developed by researchers at the University of Pittsburgh's Human Engineering Research Laboratories (HERL) was mentioned in 19 papers (e.g. Tolerico et al., 2007); and 2) a Polar heart rate monitor, which was also mentioned in 19 papers (e.g. Sindall et al., 2013a). No other system was reported in more than nine papers.

DISCUSSION

To our knowledge, this work represents the first attempt to synthesize the literature on data logger technologies for manual wheelchairs. As proposed by Grant and Booth (2009), this scoping review is not a final output, but is part of a process which ultimately aims to help to further the development and increase the functionality of data loggers with wheelchairs. This scoping review identified articles that presented a wide variety of data logging systems and sensing technologies, and measured a wide range of outcomes. Technologies such as accelerometers, odometers and heart monitors, and outcomes related to kinematics (distance, speed/velocity, and acceleration), mobility events, heart rate and driving time were the most common. To some extent, this diversity may be attributed to the fact that 59 of the logging devices (64.8%) were reported only once, which may be explained by one of these three reasons: 1) some systems may have been developed with an engineering perspective and without further action pursued (i.e. no demonstration of their validity or intention to use them in the context of experimental studies), 2) some systems may have been modified over time (e.g. name of the system, some of its components, etc.), so each "version" is considered as a different system, and 3) some systems may have been developed very recently and other studies (developmental or experimental) are currently underway. In order to develop flexible systems with increased functionality and applicability for manual wheelchairs, the research community should focus its efforts on a limited number of well-described custom-built systems, like the ones developed at the University of Pittsburgh (HERL) (Tolerico et al., 2007) or at the Georgia Institute of Technology (Sonnenblum, Sprigle, Caspall, & Lopez, 2012), rather than starting from scratch every time. A flexible data logging device that can measure an assortment of outcomes and can integrate different commercial sensors, which

make it easy to measure specific variables, is potentially very promising for a variety of uses. The development of such a system remains an important challenge from a research perspective. In the future, technological developments and decreasing costs of data loggers and sensing technologies may make it possible to easily measure many significant outcomes.

Since the majority of the analyzed papers (n=83; 69.7%) were very recent (published between 2010 and 2015), a gap may exist between the research currently underway in the field of manual wheelchair data logging and the works that have appeared in the literature. For example, in this scoping review only a few papers (n=8) presented systems that included GPS localization (e.g. Chen, Harniss, Patel, & Johnson, 2014; Dewancker, Borisoff, Jin, & Mitchell, 2014; Jayaraman, Deeny, Eisenberg, Mathur, & Kuiken, 2014; Sindall et al., 2013b; Xu et al., 2010), but the proliferation of GPS receivers in smartphones and fitness systems over the last few years makes it plausible that this technology could become much more common in the next generation of data loggers. Smartphones and cloud-based data storage and processing are computing platforms which offer great potential for personal data logging, combining accelerometers, GPS, and other embedded sensors, along with the potential for processed data and visualization tools. Moreover, the proliferation of fitness (wrist or waist worn) and smartwatch systems such as *Fitbit* (2016), *ActiGraph* (2016) or *Jawbone UP* (2016) offer the potential for easier access to data logging technology for wheelchairs. However, while these commercial systems come with algorithms to estimate steps taken and general activity levels in ambulating individuals, research will need to show their applicability to wheelchair use in the community. Although there is some literature on the use of *ActiGraph* (García-Massó et al., 2013; García-Massó et al., 2015; Learmonth, Kinnett-Hopkins, Rice, Dysterheft, & Motl, 2016; Nightingale, Walhim, Thompson, & Bilzon, 2014; Nightingale et al., 2015), more studies are required to document its validity and applicability with manual wheelchairs.

In this review we have omitted systems that were only reported as being used in the laboratory, although perhaps they could be used beyond. For instance, we did not include papers which used only SMARTWheel or similar systems, based on the following reasoning: 1) data recorded by these devices in typical community use has not been reported (to our knowledge); and 2) they are unlikely to be used in the community context for practical reasons (they are expensive, delicate and have limited memory storage capacity).

From a clinical perspective, this scoping review represents a first step to describe the gap between existing systems and the possibility for the clinicians to use them. In our opinion, the vast majority of the identified systems may not be easy to use in the clinical context: besides potentially complicated installation, interpreting the results in the format in which they are provided may represent another issue which must be addressed by developers. Moreover, there is a need to identify what outcomes are useful for clinicians and researchers, as suggested in part by Hoenig, Giacobbi, and Levy (2007). To address this issue, based on the results from this scoping review, we have developed an online survey to query clinicians and researchers about which variables are most important when objectively documenting manual wheelchair use with data logger technologies, how outcomes should be measured, and some of the challenges and barriers clinicians and researchers may experience when using data loggers. The results will be presented in another scientific paper.

This study has some limitations. First, it is acknowledged that the quality of the studies retained for this scoping review has not been assessed. As described in Arksey and O'Malley (2005), scoping reviews seek only to capture the breadth of literature on a specific research area, in contrast to systematic reviews which aim to assess the quality and depth of literature linked to a specific research question. Levac et al. (2010) pinpointed the challenges in assessing the quality among the vast range of literature included in a scoping review. Second, although they were chosen carefully, the keywords are perhaps not exhaustive, and some relevant papers may not have been identified by the literature search. Third, we may have overlooked some grey literature. Google Scholar provided a vast amount of search results, even when a refined keyword list was used, and it proved difficult to assess all of them. Fourth, we did not do a directed search of the references listed within each of the selected studies. Finally, only one reviewer led the screening of the results obtained from the databases and Google Scholar and selected most of the papers for this scoping review. Therefore, the list of the papers retained for this review did not come, in its entirety, from an agreement process between reviewers.

CONCLUSION AND FUTURE WORK

Over the past two decades, data loggers have increasingly been used to provide innovative and quantitative documentation of wheelchair users' activities by recording a variety of outcome measures. Indeed, our findings show a wide variety of data logging systems and sensing technologies measuring a whole range of outcomes; consequently, the development of a flexible, valid and user-friendly system for the objective assessment of manual wheelchair use is still a challenge. However, we think that dropping costs and improving technology are likely to bring data loggers into widespread clinical (and even personal) use. It is also not clear whether the most commonly measured outcomes of today's data loggers are the most suitable for widespread use – perhaps they are merely the easiest to measure. As the relevant technologies continue to improve, we feel it may be time to discuss which outcomes are most important, as well as which methods are best for analyzing and displaying the outcomes to those using data loggers. As a first step to identifying which outcomes are most interesting to researchers and clinicians when attempting to objectively document manual wheelchair use, we have developed an online survey. Finally, another analysis similar to the one presented here is underway to provide an overview of the literature reporting the objective assessment of powered wheelchair use through data logger systems.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.
Flow diagram for study selection

Table 1

Publication date of the selected papers

Publication date	# of papers	% of total papers
1985–1989	2	1.7
1990–1994	3	2.5
1995–1999	0	0
2000–2004	9	7.6
2005–2009	22	18.5
2010–2015	83	69.7
TOTAL	119	

Table 2

Sensing technologies reported in the selected papers

Sensing technologies	# of times reported	technologies (n=217)
<u>On the wheelchair</u>		
1. Odometer	27	12.4
2. Accelerometer	21	9.7
3. Gyroscope	12	5.5
4. Pressure sensors/switch	11	5.1
5. Force sensing technology	11	5.1
6. GPS (outdoor)	6	2.8
7. Wireless positioning system (indoor)	5	2.3
8. Temperature sensors	4	1.8
9. Electrocardiogram	3	1.4
10. Potentiometer	2	0.9
Other sensors	8	3.7
Total: Technologies on the wheelchair	110	50.7
<u>On the user</u>		
1. Accelerometer	41	18.8
2. Heart monitor	21	9.7
3. Thermistors	9	4.1
4. Metabolic cart	9	4.1
5. Near body temperature sensor	6	2.8
6. Galvanic skin response sensor	6	2.8
7. Electrocardiogram	3	1.4
8. Gyroscope	2	0.9
9. Force sensing technology	2	0.9
10. Wireless positioning system (indoor)	2	0.9
11. GPS (outdoor)	2	0.9
12. Respiration monitors	1	0.5
13. Oximeter	1	0.5
14. Compass	1	0.5
15. Temperature sensors	1	0.5
Total: Technologies on the user	107	49.3
TOTAL	217	

Table 3

Outcomes measured by the logging devices reported in the selected papers

Outcomes	# of papers reporting the outcome	# of times measured*	% of total outcomes measured (n=433)
Distance	38	47	10.9
Mobility events	36	45	10.4
Heart rate	24	42	9.7
Speed/Velocity	36	39	9.0
Acceleration	27	35	8.1
Driving time	21	27	6.2
Respiration	11	22	5.1
Seat pressure	9	19	4.4
Body temperature	8	16	3.7
Angular velocity	10	13	3.0
Position	7	11	2.5
Forces/Torque/Power	6	10	2.3
Pressure-relief activities	5	8	1.8
Body posture	7	7	1.6
Strokes	4	7	1.6
Duration at different speeds	6	6	1.4
Orientation	4	6	1.4
Sitting time	3	6	1.4
Wheel angular position and revolutions	5	5	1.2
Seat temperature and humidity	4	5	1.2
Vibration exposure of wheelchair users	3	3	0.7
Others: Physiological outcomes	20	44	10.2
Others: Mobility outcomes	7	10	2.3
TOTAL	301	433	

* The same paper can report outcomes such as distance traveled and maximum distance of continued movement, which are grouped into the “distance” outcome category. Thus, for this example, the number of papers reporting the outcome is one and the number of times the outcome was measured is two (Tolerico et al., 2007).

Table 4

Outcomes measured and location of the sensing technologies

Outcomes	# of times measured	# of times obtained from sensing technology on the wheelchair	# of times obtained from sensing technology on the user	# of times obtained from sensing technology on the wheelchair AND the user
Distance	47	44	2	1
Mobility events	45	17	24	4
Heart rate	42	0	42	0
Speed/Velocity	39	38	1	0
Acceleration	35	8	24	3
Driving time	27	23	3	1
Respiration	22	2	20	0
Seat pressure	19	19	0	0
Body temperature	16	0	16	0
Angular velocity	13	10	3	0
Position	11	6	1	4
Forces/Torque/Power	10	6	4	0
Pressure-relief activities	8	7	1	0
Body posture	7	2	5	0
Strokes	7	1	0	6
Duration at different speeds	6	6	0	0
Orientation	6	6	0	0
Sitting time	6	6	0	0
Wheel angular position and revolutions	5	5	0	0
Seat temperature and humidity	5	5	0	0
Vibration exposure of wheelchair users	3	3	0	0
Others: Physiological outcomes	44	16	27	1
Others: Mobility outcomes	10	3	5	2
TOTAL	433	233	178	22

Table 5

Definitions of the measured outcomes representing at least 2.0% of the total

Outcomes	Definitions
Distance	Includes measures such as distance travelled in the wheelchair and maximum distance of continuous movement.
Mobility events	Includes measures such as counts of continuous segments of movement of the wheelchair, movement bouts or activity counts, duration of dynamic activities as a percentage of a 24-hour period.
Heart rate	Includes various measures of heart rate, peak heart rate, heart rate reserve, physical strain, etc. May be measured continuously or averaged. May be measured while propelling, while resting, or at all times.
Speed/Velocity	Rate at which the wheelchair moves or changes its position, continuously or averaged.
Acceleration	Rate of change of velocity or speed of the wheelchair.
Driving time	Includes such measures as time spent moving the wheelchair (i.e. pushing or wheeling), time spent operating a wheelchair, percent of time in the wheelchair spent wheeling and maximum time of continuous movement.
Respiration	Includes such measures as respiratory rate, oxygen saturation, oxygen consumption (VO_2) and carbon dioxide production (VCO_2).
Seat pressure	Includes such measures as weight distribution and pressure maps of sitting postures. May be measured continuously or averaged. May be measured while propelling, while resting, or at all times.
Body temperature	Includes measures such as skin, aural, body surface, core temperature or heat storage.
Angular velocity	Rate of angular displacement of the wheelchair or of the user (e.g. of the trunk).
Position	Includes measures obtained via a wireless positioning system (indoor) or a Global Positioning System (outdoor).
Forces/Torque/Power	Includes measures of propulsion forces, torque, or power, total drag forces and contact forces over the hand's surface.