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Appendix 1. PubMed search strategy.

The following search strategy was used for PubMed and modified for other databases.

1. manual wheelchair user*
2. manual wheelchair
3. wheel chair
4. wheelchair*
5. OR/#1 – #4
6. monitor*
7. activity monitor
8. physical activity monitor*
9. commercial monitor*
10. portable monitor*
11. wearable monitor*
12. accelerometer*
13. gyroscope*
14. heart rate monitor*
15. heart rate sensor*
16. motion sensor
17. multisensor
18. multi sensor
19. OR/#6 – #18
20. activit*
21. physical activity
22. daily activity
23. free living activit*
24. exercise
25. ADL*
26. activity of daily living
27. sport
28. OR/#20 – #27
29. #5 AND #19 AND #28
30. publication dates filer [remove prior to 1999]/#29
31. article types filter [remove review, meta-analysis]/#30
32. subject area filter [remove articles in unrelated subject areas]/#31

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Appendix 2. Overview of the commercial and custom monitors.

Device Name	Sensors	Manufacturer	Placement Reported in Studies	Sampling Rate	Data Storage	Default Outputs
Commercial Monitors						
Uniaxial Accelerometer-based Monitor						
CSA Model 7164 monitor [38]	Uniaxial accelerometer	ActiGraph, Pensacola, FL (Formerly known as Computer Science and Applications, Inc.)	Wrist	Every 1 min	22 days	Uniaxial activity count
Triaxial Accelerometer-based Monitor						
Actiwatch [26]	Triaxial accelerometer	Mini Mitter Company, Bend, OR	Wrist	Every 15 s	30 days (1 min epoch)	Activity counts in 3 directions
ActiGraph GT3X or ActiGraph GT3X+ [32, 33, 48-51]	Triaxial accelerometer, ambient light photodiode	ActiGraph, Pensacola, FL	Ankle, waist, wrist	30 Hz **GT3X+ has sampling rates range from 30 – 100 Hz (10 Hz increment)*	20 days	Accelerations in 3 directions, vector magnitude, activity counts, steps, amount of ambient light, energy expenditure (EE), and metabolic equivalent of tasks (METs)
GENEActiv [51]	Triaxial accelerometer, light sensor, linear active thermistor	Activinsights, Cambridge, UK	Wrist	10 Hz–100 Hz	45 days (at 10 Hz)	Signal vector magnitude, raw accelerations in 3 directions, temperature, METs
activPAL trio physical activity monitor [36]	Triaxial accelerometer	PAL Technologies Ltd, Glasgow, UK	Spokes of a rear wheel	10 Hz	10 days	Accelerations in 3 directions
RT3 [27, 28]	Triaxial accelerometer	Stayhealthy Inc., Monrovia, CA	Upper arm over triceps, waist	1 Hz	21 days	Activity count in 3 directions, resultant activity count, total EE

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PowerTap SL + Track hub [30]	Eight strain gauges	Saris Cycling Group, Madison, WI	On a wheel hub	60 Hz	Not provided	Torque, power, speed, distance
Multisensor-based Monitor						
Sensewear [24, 25, 27, 29, 34, 35]	Tri-axial accelerometer (2-axis in early models), galvanic skin response sensor, skin temperature sensor, and near body temperature sensor	Bodymedia Inc., Pittsburgh, PA *Note: Now is Jawbone, San Francisco, CA*	Upper arm over triceps	16 Hz (accelerations) Every 1 min (skin temperature, nearbody temperature, galvanic skin response, and energy expenditure)	14 days	Accelerations in 3 directions, skin temperature, galvanic skin response, nearbody temperature, steps, METs, and energy expenditure
Other						
Polar heart rate monitor [31, 35, 37, 51]	Heart rate sensor	Polar Electro, Finland	Chest	Every 5 s – 1 min	Not provided	Heart rate (beat/min)
Custom Monitors						
Activity Monitor by Postma et al. (2005) [47]	Component 1: ADXL 202 Piezo-resistive triaxial accelerometers (Analog Devices, Breda) Component 2: Portable Vitaport3™ data recorder (Temec Instruments, Kerkrade, The Netherlands)	The Erasmus University Medical Center, The Netherlands	Accelerometers: thigh, wrist, chest Portable recorder: waist	32 Hz	Not provided	Accelerations in 3 directions
Motion sensor device by Kiuchi et al. (2014) [46]	Component 1: Tri-axial accelerometer (MiscroStone Corporation, Nagano, Japan) Component 2: Gyro sensor	Ochanomizu University, Bunkyo, Tokyo, Japan	Upper arm over triceps, wrist	200 Hz	Not provided	Accelerations in 3 directions, angular velocity
Monitoring device by Ojeda et al. (2014) [39]	Component 1: Triaxial accelerometer (Shimmer Research, Dublin)	Human Engineering Research Laboratories,	Component 1: Upper arm, wrist Component 2:	Component 1: 20Hz or 60 Hz Component 2: passive monitoring	Not provided	Accelerations in 3 directions, wheel rotation

	Component 2: Wheel rotation monitor that uses reed switches and a magnet (Human Engineering Research Laboratories, University of Pittsburgh)	University of Pittsburgh, PA,	Spokes of a rear wheel			
Gyroscope-based wheel rotation monitor (G-WRM) by Hiremath et al. (2013) [40]	Reed switches and a magnet, a bi-axial gyroscope	Human Engineering Research Laboratories, University of Pittsburgh, PA,	Spokes of the rear wheel	64 Hz to 1sample/min	Not provided	Angular velocities
GPS tracking device with integrated accelerometer by Sindall et al. (2013) [41]	Component 1: Portable GPS tracking device with integrated accelerometer (SPI Elite™, GPSports System, Canberra, Australia) Component 2: Wheel rotation monitor that uses reed switches and a magnet (Human Engineering Research Laboratories, Pittsburgh, USA)	The University of Salford, Salford, UK	Component 1: Back of the seat Component 2: Non-racquet side of the rear wheel of tennis wheelchair	Component 1: 1 Hz for GPS, 100 Hz for accelerometer Component 2: passive monitoring	Not provided	Position, speed of wheel rotation
Triaxial accelerometer by Sonenblum et al. (2012) [42]	Component 1: Tri-axial MEMS accelerometer (Freescale MMA7260Q) Component 2: Data logging system that was built around Microchip's P1C18LF2331 microcontroller	Rehabilitation Engineering and Applied Research Laboratory, Georgia Institute of Technology, GA, USA	Spokes of rear wheel	60 Hz	Not provided	Acceleration in 3 directions, rotation angle, revolution, active time (s)

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Wheelchair propulsion monitoring device by Ding et al. (2011) [43]	Component 1: eWatch that uses a triaxial accelerometer Component 2: Wheel rotation monitor that uses reed switches and a magnet	Component 1: Human Computer Interaction Institute, Carnegie Mellon University Component 2: Human Engineering Research Laboratories, University of Pittsburgh	Component 1: Dominant wrist Component 2: Spokes of the rear wheel	Component 1: 20 Hz Component 2: passive monitoring	Not provided	Wheelchair velocity, accelerations in 3 directions
PushTracker by Turner, W.E.J. (2011) [44]	Component 1: Accelerometer Component 2: Magnet Component 3: Magnet sensor	Turner & W.E.J.	Component 1 & 2: Axle of the rear wheel Component 3: Distal end of the axle of the rear wheel (within the frame)	Not provided	Not provided	Distance, speed, number of propulsion (pushes), cadence (pushes/min)
Telemetry-based velocometer by Moss et al. (2003) [45]	Component 1: Optical encoder (HEDS-5700A00) Component 2: FM transmitter with antenna	Manchester Metropolitan University, Stoke-on-Trent, UK	Rear wheel of a racing wheelchair	200Hz	Not provided	Wheel rotation, accelerations in 3 directions
Physical Activity Monitoring System (PAMS) by Hiremath et al. (2015) [53]	Physical activity monitoring system (PAMS) contains: Component 1: a gyroscope-based wheel rotation monitor Component 2: an accelerometer device	Human Engineering Research Laboratories, University of Pittsburgh	Component 1: spokes of wheel Component 2: upper arm or wrist	Component 1: 64 Hz Component 2: 40 Hz	Not provided	Angular velocity, accelerations in 3 directions

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Appendix 3. Characteristics of six studies that evaluated commercial monitors with default algorithms.

Study (Year)	Diagnoses (Number of MWUs)	Monitor (Placement)	Setting: Activity	Length of Trial	Outcome Measures
Tanhoffer et al. (2015)	SCI C6 – T12 (n=8)	Sensewear (Right upper arm over triceps)	Clinical Exercise and Rehabilitation Unit: arm-crank ergometry, wheelchair treadmill, hand-cycling, pushing their own wheelchair outdoors Home: Any activities other than shower	14 days	Total Daily EE (kJ/day), Physical Activity EE (kJ/day), physical activity types (sedentary or exercise)
Hiremath et al. (2012)	SCI T3 or above (n=7), T4 or below (n=38) *Total: 45*	Sensewear (Right upper arm over triceps)	Lab: resting, wheelchair propulsion (including 2mph and 3mph on a computer-controlled dyno, 3mph on a flat tile), arm-ergometer exercise (including 40rpm at 20W, 60rpm at 40W, 90rpm at 40W), deskwork (including reading a book and typing on a computer)	3 hours	EE (kcal/min)
Perez-Tejero et al. (2012)	Stroke (n=9), spina bifida (n=5), paraplegia (n=7), traumatic brain injury (n=3), polio (n=2), rheumatoid arthritis (n=1), multiple sclerosis (n=1), osteoarthritis in both knees (n=1) *Total: 29 (Only 8 of them were MWUs)*	Sensewear (Dominant upper arm over triceps)	Home: life and sports activities for 7 days.	7 days	Duration of PA, MET, active EE
Hiremath et al. (2011 – a)	SCI T3 – L4 (n=24)	Device 1: RT3 (waist) Device 2: Sensewear (Right upper arm over triceps)	Lab: resting, wheelchair propulsion (including 2mph and 3mph on a computer-controlled dyno, and 3mph on a flat tile surface), arm-ergometer exercises (including 60rpm at 20W, 60rpm at 40W and 90 rpm at 40W), and deskwork (including reading and typing on a computer)	4 hours	EE (kcal/min)

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Hiremath et al. (2011 – b)	SCI T3 – L4 (n=24)	RT3 (Left upper arm over triceps, waist)	Same study protocol as above (Hiremath et al. 2011 – a)	4 hours	EE (kcal/min)
Warms et al. (2004)	SCI C6 – C8 (n=6), T1 – T5 (n=6), T6 – T12 (n=6), L1 – S45 (n=4) *Total: 22*	Actiwatch (Non dominant wrist)	Lab: "active" activities (including wheelchair propulsion on a level indoor surface, upper extremity range-of-motion exercises) and "inactive" activities (sitting quietly with arms in the lap and sitting at a desk doing keyboarding activities) Field: home activities	Lab: 20 mins Field: 8 days	Activity count (counts/day)

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Appendix 4. Characteristics of 15 studies that evaluated commercial monitors with custom algorithms.

Study (Year)	Diagnoses (Number of MWUs)	Monitor (Placement)	Setting: Activity	Length of trial	Outcome Measures
Garcia-Masso et al. (2015)	SCI T4 – S1 (n=20)	ActiGraph GT3X (Dominant sides of chest and waist, and both wrists)	Lab: lying down, body transfers, moving items, mopping, working on a computer, watching TV, arm ergometer exercise, passive propulsion, slow propulsion, and fast propulsion	120 mins	Physical activity types (sedentary, transfers, housework, locomotion, moderate physical activity)
Learmonth et al. (2016)	SCI (n=10), spina bifida (n=5), multiple sclerosis (n=2), amputation (n=2), congenital bone disorder (n=2), cerebral palsy (n=1), demyelinating disease (non-multiple sclerosis, n=1) *Total: 22 (one person has 2 diagnoses)*	ActiGraph GT3X (both wrists)	Lab: sitting quietly, wheelchair propulsion on a motor-driven wheelchair treadmill (1.5mph, 3.0mph, 4.5mph)	60 mins	Activity counts
Nightingale et al. (2015)	SCI T1 – L4 (n=10), spina bifida (n=3), cerebral palsy (n=1), scoliosis (n=1), bilateral amputee (n=1) *Total: 16*	Device 1: ActiGraph GT3X+ (Right upper arm and wrist) Device 2: GENEActiv (Right upper arm and wrist) Device 3: Polar Team HR monitor (chest)	Lab: resting, folding clothes, propulsion on a 1% gradient (3, 4, 5, 6, 7km/h), propulsion at 4km/h (with additional 8% body mass at 2% and 3% gradients) on a motorized wheelchair treadmill.	90 mins	Physical activity EE (kcal/min)
Kooijmans et al. (2014)	SCI C6 and higher (n=2), C7 and below (n=8)	ActiGraph GT3X+ (Wrist, spokes of the wheel)	Lab: wheelchair driving on a treadmill (1km/h, 2km/h, 4km/h), wheelchair driving on a slope on a treadmill	15 mins	Physical activity types (self-wheelchair propulsion and non-wheelchair propulsion

	Total: 10		(4km/h), wheelchair driving on a flat ground (slow, normal, fast speed), hand cycling on a flat ground (fast speed), being pushed (with participants' arms hanging still, with arms moving), turning around or changing from position in the area, sitting still Simulated apartment: opening the door driving through and closing the door, transfer to bed, laying supine in bed, driving around in the apartment, putting on a coat, hand cycling outdoors		activities)
Conger et al. (2014)	SCI T1 – T4 (n=2), T5 – T12 (n=5), spina bifida (n=4), amputation (n=2), Charcot-Marie-Tooth (n=1) *Total: 14*	Device 1: PowerTap SL + Track hub (Rear wheel hub) Device 2: Polar heart rate monitor (Chest)	Lab: propulsion on a level surface that elicited a low rolling resistance at three different speeds (4.5, 5.5 and 6.5 km/h), propulsion on a rubberized 400 m track that elicited a higher rolling resistance at one speed (5.5 km/h) and propulsion on a sidewalk course that included uphill and downhill segments at a self-selected speed.	75 mins	Torque (Nm), speed (km/h), power (W), distance (km), and heart rate (bpm)
Coutinho et al. (2014)	SCI C6 – C8 (n=15), T1 – T6 (n=17), T7 – L3 (n=16) *Total: 48*	Polar heart rate monitor (Chest)	Lab: rest at sitting position, propulsion at self-selected speeds in a closed paths (with a diameter of 30 or 70 m)	10 mins	Three heart rate indexes including Physiological Cost Index, Total Heart Beat Index, Propulsion Cardiac Cost Index
Nightingale et al. (2014)	SCI T4 or below (n=9), fibromyalgia (n=1), complex regional pain syndrome (n=1), spina bifida (n=2) *Total: 13*	Actigraph GT3X+ (Right upper arm, right wrist, right side of waist)	Outdoor athletics track: propelling wheelchair at 2, 4, 6, and 8 km/h Indoor: deskwork (typing a script)	1 hour	PAEE (kJ/min)

Garcia-Masso et al. (2013)	SCI T2 – L5 (n=20)	ActiGraph GT3X (Non-dominant side of waist and chest, left and right wrists)	Lab: lying down, body transfer, moving items, mopping, watching TV, working on a computer, arm-ergometry exercise, passive propulsion, slow propulsion, and fast propulsion at self-selected speed	2 hours	VO_2 (ml /kg/min)
Hiremath et al. (2013)	SCI T3 or above (n=7), T4 or below (n=38) *Total: 45*	Sensewear (Right upper arm over triceps)	Lab: resting, wheelchair propulsion (including 2mph and 3mph on a computer-controlled dyno, 3mph on a flat tile), arm-ergometer exercise (including 40rpm at 20W, 60rpm at 40W, 90rpm at 40W), deskwork (including reading a book and typing on a computer).	3 hours	EE (kcal/min), Physical activity types (resting, propulsion, arm ergometry, and deskwork)
Hiremath et al. (2012)	SCI T3 or above (n=7), T4 or below (n=38) *Total: 45*	Sensewear (Right upper arm over triceps)	Same experimental protocol as Hiremath et al. (2013)	3 hours	EE (kcal/min)
Tanhoffer et al. (2012)	SCI C4 – T12 (n=14)	Device 1: Polar heart rate monitor (Chest) Device 2: Sensewear (Right upper arm)	Lab: Lying down, sitting in their wheelchairs, propel on treadmill at 6 different velocities (from 1 km/h to 3.5 km/h) at a constant grade (0.5% slope) and a constant velocity (2 km/h) at 6 different grades (0.5% to 3% slope) Field: household chores, work-related activities, and leisure activities	2 days	TDEE (kJ/day), PAEE (kJ/day)

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Coulter et al. (2011)	SCI C6 – L3 (n=11)	activPAL trio physical activity monitor (Spokes of a rear wheel)	Indoor: propelled over a circular track at self-selected speed Outdoor: propelled at self-selected speed on a course incorporating forward and backward movement, ramp maneuvers with gradients of 5 and 20° (n=2), obstacle maneuvers with left and right turns (n=2), 3.6m gravel path (n=1) and 10–13cm height curbs (n=1).	500 secs	Absolute Angle (degree), wheel revolutions (cycle), and duration of movement (s)
Hiremath et al. (2011)	SCI T3 – L4 (n=24)	RT3 (Left upper arm over triceps, waist)	Lab: resting, wheelchair propulsion (including 2mph and 3mph on a computer controlled dynamometer, and 3mph on a flat tile surface), arm ergometer exercise (including 60rpm at 20W, 60rpm at 40W and 90rpm at 40W), and deskwork (including typed on a computer and read a book of their choice).	3 hours	EE (kcal/min)
Lee et al. (2010)	SCI T6-L4 (n=27)	Polar heart rate monitor (Chest)	Lab: 30 min resting, working on a computer, sitting and watching TV, vacuuming, moving chairs, pushing the wheelchair on tiled surface, sidewalk, and up and down a ramp, arm ergometer exercise	100 mins	Individual and group calibrated METs
Washburn and Copay (1999)	SCI T4 – T12 (n=11), spina bifida (n=7), osetogensis imperfecta (n=1), polio (n=1), dystonia (n=1) *Total: 21*	CSA Model 7164 uniaxial accelerometer (Left and right wrists)	Rectangular indoor course: wheelchair propulsion at slower than normal, normal, and faster than normal speed.	1 hour	VO_2 (ml/kg/min), propulsion frequency (strokes/min)

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Appendix 5. Characteristics of 10 studies that quantified physical activity in manual wheelchair users with custom devices and algorithms.

Study (Year)	Diagnoses (Number of MWUs)	Monitor (Placement)	Setting: Activity	Length of trial	Outcome Measures
Hiremath et al. (2015)	SCI (n=45)	Physical activity monitoring system (PAMS) contains: Component 1: a gyroscope-based wheel rotation monitor (spokes of wheel) Component 2: an accelerometer device (upper arm or wrist)	Lab, National Veterans Wheelchair Game (NVWG): resting, propelling wheelchair on a tile surface (medium, fast speed), propelling on a medium pile carpet (medium, slow speed), propelling up and down a ramp (normal speed), being pushed in a wheelchair on a tile surface or a medium pile carpet or up and down a ramp, playing wheelchair basketball, folding laundry, performing deskwork (reading, using a computer), playing darts, using a Theraband, exercising on an arm ergometer (normal speed/resistance) Home: resting, propelling in their home or community on a tile or carpet surface, watching TV, simulating eating and cooking, sweeping or vacuuming, making bed, using a dumbbells or handgrip, washing dishes and laundry, doing wheelchair pushups	Lab/NVWG: 3 hours Home: 2 hours	Physical activity types (resting, arm ergometry, household activities, wheelchair propulsion, being pushed, wheelchair basketball, wheelchair maybe moving)
Kiuchi et al. (2014)	SCI C6 – C7 (n=3), T1 – T9 (n=3) *Total: 6*	The motion sensor device (Left and right upper arms, left and right wrists), which consists of: Component 1: Triaxial accelerometer Component 2: Gyro sensor	Lab: driving wheelchair on a treadmill at rating of perceived exertion (RPE) 9 (2.5-3.0 km/h), RPE 11 (3.5-4.0km/h) and RPE 13 (4.5-5.0km/h) intensities	68 mins	EE (kcal/min/kg)

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Ojeda et al. (2014)	SCI T3 or above (n=6), T4 or below (n=20) *Total: 26*	The monitoring device, which consists of: Component 1: Tri-axial accelerometer (Dominant upper arm and wrist, and under wheelchair seat) Component 2: Wheel rotation monitor (Spokes of a rear wheel)	Lab: propelling on a flat surface at self-selected speed, low speed, and fast speed, and on a sloped (5^{o}) surface at self-selected speed	Two lab visits: 5 hours	Number of propulsion, propulsion frequency (stroke/s)
Hiremath et al. (2013)	SCI (n=1)	Gyroscope-based wheel rotation monitor (Spokes of the rear wheel)	Lab: Wheelchair propulsion (forward and backward) tests. Outdoor cycling track: Hand-cycling test (9 laps on asphalt concrete surface)	N/A	Angular velocity (rpm), linear speed (m/s), distances travelled (m)
Sindall et al. (2013)	Wheelchair tennis players (n=15) *Note: Diagnoses were not reported.*	Component 1: Portable GPS tracking device with integrated accelerometer (Back of the seat) Component 2: Datalogger (Non-racquet side of the rear wheel of tennis wheelchair)	Field: Wheelchair tennis match (2010 Wheelchair Tennis British Open in Nottingham, Britain), tennis drills on the court	N/A	Distance travelled (m)
Sonenblum et al. (2012)	SCI (n=2)	Tri-axial MEMS accelerometer (Spokes of rear wheel)	Lab: (Indoor activities of daily living) Navigating typical indoor environment, i.e. kitchen, bathroom and hallways, food preparation, handwashing, loading a dishwasher, entering a bathroom stall, using an elevator, and traversing a straight 23 m hallway 3 times.	30 mins	Physical activity types (wheelchair is moving or being stationary), distance wheeled (m)
Ding et al. (2011)	SCI C4 – L5 (n=19); Multiple Sclerosis (n=3); Amputation (n=3) *Total: 25*	Wheelchair Propulsion Monitoring Device, which consists of: Component 1: eWatch (Dominant wrist)	National Veterans Wheelchair Games: The ADL trials included resting, propelling their wheelchair over different surfaces and terrains, being pushed by an investigator, typing on a	N/A	Physical activity types (self-propulsion, external pushing, and sedentary activity)

		Component 2: Wheel rotation datalogger (Spokes of the rear wheel)	computer, reading, doing laundry, folding clothes, preparing meals, and transferring between their wheelchair and a chair. The wheelchair propulsion trials included propelling on a low profile carpet, and propelling up and down a ramp at three different cross slope angles (i.e., 0°, 1°, and 2°) and two different slope angles (i.e., 0° and 5°) on wood, blind guide, and Telfon drizzled with soapy water. All trials were performed at self-selected pace.		
Turner, W.E.J. (2011)	MWUs (n=10) *Note: Diagnoses were not reported.*	PushTracker (Axle of the rear wheel)	Lab (over-ground test course): propulsion on surfaces including asphalt, sidewalk concrete, low-pile carpet, and cement.	N/A	Distance (m), speed (m/s), number of propulsion (pushes), propulsion frequency (pushes/min)
Postma et al. (2005)	SCI C6 – L5 (n=10)	The Activity Monitor, which consists of: Component 1: ADXL 202 piezo-resistive accelerometers (Left and right thigh, left and right wrist, and chest over sternum) Component 2: Portable Vitaport3^{TM} data recorder (Waist)	Semi-natural setting (hallway of the rehabilitation center, and an apartment used for therapy and exercise): wheelchair propulsion (hand-rim wheelchair propulsion and hand biking) indoors in large and small areas and outdoors, open/close door, leaf through magazine, preparing and eating sandwich, washing dishes, transfer, donning a coat, and other everyday life activity.	45 mins	Physical activity types (non-propulsion vs propulsion), duration of propulsion (sec)
Moss et al. (2003)	Total wheelchair user (n=1) *Note: Diagnosis was not reported*	Telemetry-based velocometer (Rear wheel of a racing wheelchair)	Lab: propulsion using a racing chair on a motor driven treadmill at 1, 5 and 9 m/s. Propulsion when the treadmill accelerated from 0m/s to 9.5m/s and decelerated from 9.5m/s to 0m/s. Propulsion of 15meteres with only pushing for first 5 meters.	N/A	Wheelchair velocity (m/s)