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Holistic Sensor-Based Approach for Assessing Community Mobility and Participation of Manual Wheelchair Users in the Real World

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Abstract: Given the unique challenges faced by manual wheelchair users, improving methods to accurately measure and enhance their participation in community life is critical. This study explores a comprehensive method to evaluate the real-world community mobility and participation of manual wheelchair users by combining GPS mobility tracking, heart rate, and activity journals. Collecting qualitative and quantitative measures such as the life space assessment, wheelchair user confidence scale, and physical performance tests alongside GPS mobility tracking from ten manual wheelchair users provided insight into the complex relationship between physical, psychological, and social factors that can impact their daily community mobility and participation. This study found significant, strong correlations between the recorded journal time outside of the home and the GPS mean daily heart rate ($r = -0.750$, $p = 0.032$) as well as between the upper limb strength assessments with cardiovascular assessments, physiological confidence, and GPS participation indicators ($0.732 < r < 0.884$, $0.002 < p < 0.039$). This method of manual wheelchair user assessment reveals the complex relationships between different aspects of mobility and participation. It provides a means of enhancing the ability of rehabilitation specialists to focus rehabilitation programs toward the areas that will help manual wheelchair users improve their quality of life.

Keywords: community mobility; community participation; manual wheelchair user; wearable sensors; activity journal; life space assessment

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1. Introduction

Wheelchair users comprise a substantial proportion of the world's population, with 3.3 million living in the United States [1]. Regular wheelchair use can significantly impact an individual's community mobility and participation (CMP). Ensuring clinicians have an effective means of accurately and quickly assessing the CMP of manual wheelchair users (MWUs) is crucial for improving their lives. Community mobility is the ability of an individual to move around within the community and engage in various activities. In contrast, community participation is an individual's involvement in societal activities within the community [2]. Community mobility allows wheelchair users to engage in physical activities that help maintain their physical health and fitness and improve their functioning, confidence, and general community participation [3,4]. CMP has been shown to play a crucial role in the physical and mental well-being and quality of life of wheelchair users [5–7].

Due to a typically sedentary lifestyle [8,9], regular movement and physical activity are essential in preventing secondary health issues for MWUs, such as pressure sores, cardiovascular disease, and musculoskeletal problems [3,4]. This is especially important to

MWUs as they have an increased rate of injury risk when compared to powered wheelchair users [10–12]. Rehabilitation specialists must be able to effectively and easily monitor their patients' CMP to best assign treatments and therapy for recovery.

One of the typical ways that the CMP of MWUs has been assessed is through in-clinic tests for self-propelled velocity, strength, physical fitness, and exercise, all of which are indicators of CMP [2]. Physical fitness is evaluated through tests like the 6-min push test (6MPT) for MWUs, where the MWU propels themselves as far as they can in 6 min [13]. The test provides insights into cardiovascular health and overall fitness levels, essential for daily functioning and mobility [14]. Muscle strength and endurance are often evaluated through an isokinetic dynamometer, which measures strength during specific movements [11]. Researchers have used this to evaluate the upper body strength of wheelchair users, which is essential for propelling the wheelchair and performing daily activities [11,15]. However, while in-clinic measurements are precise, they only represent a moment in time and do not always reflect the real-world day-to-day life of the participant. They are also often conducted in controlled environments, which may not fully reflect the challenges and facilitators presented in daily life.

An alternative to in-clinic testing is remote measurement, which can be done via self-surveys, activity journals, and questionnaires such as the Life Space Assessment (LSA) [16] and Wheelchair Use Confidence Scale (WheelCon) [17]. The LSA asks questions about where the individual has been active, and how far away from their home they have traveled recently [16]. The WheelCon asks questions regarding how confident the individual is when maneuvering in their wheelchair in different situations as well as their confidence in their social and professional life [17,18]. However, self-surveys and activity journals lack both precision and reliability due to the participant's "limitations in recall ability and possibilities of perception bias" [2,19]. The advantage of remote assessment is that it allows for easier assessment without the need for patients to come into the clinic. Furthermore, remote assessment better reflects the conditions and challenges faced in the day-to-day life of MWUs [2].

Another means of remote measurement comes in the form of accelerometer and GPS devices, which have been shown to provide promising real-world data [20–22]. Previous research has demonstrated that CMP indicators can be tracked with a GPS device in healthy people through a study conducted during the COVID-19 pandemic over ten months [23]. Additionally, one previous study used GPS and accelerometer data to monitor the daily activity of four children with cerebral palsy using assistive devices over a week [24]. However, what these studies share is that they were limited to only detect the general location of the participants, giving no information about their actual engagement in the community, who they interacted with, how many, and what type of locations they visited, or how their environment may have impacted their CMP [25]. Table 1 lists existing methods, and their identified weaknesses and proposed aims in order to address them in this study.

Table 1. Related methods and their limitations.

Existing Methods and Sensor Technology	Weaknesses	Aims of This Study
6MPT [13,14]	Only captures a moment in time, does not reflect day-to-day life	Supplementing data with strength assessment, daily activities, and self-reported mobility and participation metrics.
Isokinetic Dynamometer [11,15]	Only captures a moment in time, does not reflect day-to-day life	Supplementing data with 6MPT variables, daily activities, and self-reported mobility and participation metrics.

Table 1. *Cont.*

Existing Methods and Sensor Technology	Weaknesses	Aims of This Study
Self-Surveys [2,16–19]	Limited by self-report bias and recall ability	Compare against recorded typical mobility and participation activity. Augment by in-clinic strength and mobility assessments.
Activity Journals [2,19]	Limited by self-report bias and recall ability	Compare against recorded locations visited and activity time. Augment by in-clinic strength and mobility assessments.
Accelerometers [20–22,24,25]	No locational information or data on social engagement or participation	Compare with recorded locations visited and self-reported daily activities and social participation.
GPS [20–25]	No social context for visited locations and no data on engagement or participation	Compare with self-reported locations visited, social engagement and participation. Augment by measured mobility metrics.

Previous studies have focused on individual aspects of the CMP or have utilized individual specific tools for collecting data on CMP. However, to our knowledge, there has been no comprehensive, multi-layered study conducted in a real-world setting. Our study aims to fill this gap by combining GPS mobility tracking, heart rate monitoring, and activity journals to provide a holistic understanding of MWU mobility and participation in their daily environment. This approach aims to address the limitations of previous methods and offer a multi-faceted assessment of a patient's real-world mobility, while taking into account the social and societal context of their CMP.

2. Materials and Methods

2.1. Participants

Prior to recruitment, the study protocol was approved by the University of Wisconsin–Milwaukee Institutional Review Board (protocol #24.059). The trials took place in the summer and early fall when the weather was generally warm with no extreme weather conditions present during the study. A convenient, consecutive sample of 10 MWUs (7 male, 3 female, aged 34 $\pm$ 9 years, BMI 28.8 $\pm$ 7.1 kg/m^2) were recruited for this study, 8 participants were tested at the University of Wisconsin–Milwaukee, while 2 were tested at the University of Wisconsin–Whitewater following the same study protocol. All participants were to meet the following inclusion criteria: all participants were to be age 18 and older, regularly use a manual wheelchair for daily commuting, can propel and transfer themselves independently, and had reported no history of shoulder injury within the past year. All participants were provided with written informed consent prior to participation. The demographic characteristics of the participants, including age, gender, BMI, injury type, and their wheelchair propulsion pattern are presented in Table 2.

Table 2. Participant demographics. SCI—spinal cord injury, BMI—body mass index, C—cervical, T—thoracic, L—lumbar.

ID #	Gender	Age	BMI	Injury Type	Propulsion Pattern	Occupation	Residence Type
1	Male	41	23.6	L3 Incomplete Injury	Semicircular	Engineer	Apartment
2	Male	26	32.4	T10 Incomplete Injury	Semicircular	Health and Human Services	Apartment
3	Male	32	40.8	Sacral Spina Bifida, Incomplete SCI	Arc	Student	Apartment

Table 2. *Cont.*

ID #	Gender	Age	BMI	Injury Type	Propulsion Pattern	Occupation	Residence Type
4	Male	39	29.7	T8 Complete Injury	Arc	Unemployed	Apartment
5	Male	38	19.4	T6 Complete Injury	Arc	Student	Apartment
6	Female	22	23.3	Neuromuscular Autoimmune Injury	Semicircular	Unemployed	House
7	Female	22	39.5	Spina Bifida L3, 4, 5	Semicircular	Manager	Apartment
8	Male	47	28.2	C6/C7 Incomplete	Arc	Unemployed	House
9	Female	43	28.3	Spina Bifida T12	Semicircular	Administration	House
10	Male	30	22.9	Spinal Cord T10-12 Incomplete	Semicircular	Head Coach	Apartment

2.2. Data Collection Procedures

To comprehensively assess the CMP of MWUs, a combination of quantitative and qualitative data collection tools was employed, as will be detailed below.

2.2.1. Strength Assessment

An isokinetic dynamometer was used to assess the strength of the participants. The Biodex System 4 Pro Isokinetic Dynamometer (Biodex Medical Systems, Inc., Shirley, NY, USA) and the HUMAC NORM Isokinetic Machine (HUMAC NORM by CSMi, Stoughton, MA, USA) were used to measure muscle strength and endurance of the upper body (see Figure 1A). Isokinetic dynamometers are considered the gold standard for strength assessment [26] and both the Biodex and HUMAC NORM systems have been shown to produce similar results [27]. The dynamometers were calibrated before each data collection session. A concentric/concentric bilateral shoulder and elbow strength assessment for each participant at a constant speed of 60°/s and 120°/s were performed. For this assessment, each participant was instructed to perform 5 repetitions of the 8 following muscle groups with maximum voluntary effort: the shoulder and elbow flexors, extensors, shoulder internal and external rotators, and shoulder abductors, and adductors. The participants rested for 5 min between each exercise. The torques of each isokinetic contraction at both speeds were measured. The strength assessments can provide insights into the users' physical capabilities, which are essential for wheelchair propulsion and navigation in the community [11,15].

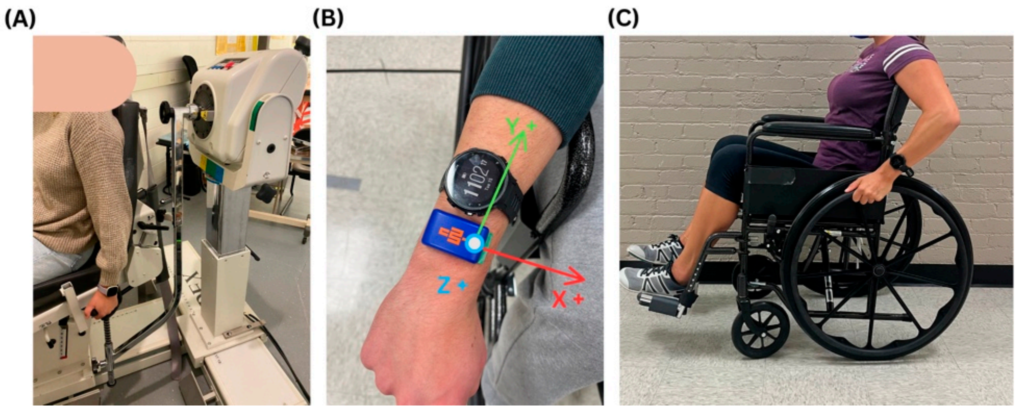

Figure 1. Equipment used. (**A**) Isokinetic dynamometer used for arm strength testing. (**B**) Garmin Forerunner 735XT GPS watch and heart rate monitor with the Vicon inertial measurement unit (IMU) showing the XYZ axes of both the accelerometer and gyroscope sensor. (**C**) Manual wheelchair and Garmin watch.

2.2.2. Mobility Performance

The 6MPT was conducted to assess the endurance and physical fitness of the participants by measuring the distances traveled in 6 min while propelling their wheelchair (see

Figure 1C). The participants were instructed to propel themselves as far and as fast as they could in 6 min while wearing inertial measurement unit sensors and a heart rate monitor (see Figure 1B). This data has been described in detail in our previous paper [28].

2.2.3. Self-Report Questionnaires

The WheelCon short form questionnaire was given to the participants to assess their confidence in their ability to use a wheelchair effectively in various environments. The total scores for the WheelCon rating were combined from the social and physical sections, with higher scores representing higher confidence with manual wheelchair use. Next, the LSA questionnaire was provided to the participants to evaluate the extent and frequency of the participants' movements within their living space, home, and community. The LSA asks the participant to mark 1 for "Yes" and 2 for "No" when answering questions on their activity, so a lower score indicates a higher level of mobility and participation.

2.2.4. Activity Journal

Participants were given a journal in paper or electronic format, according to their preference, and were instructed to fill out the journal entries every day for a week. They were instructed to fill out the activity journal and answer all the questions therein upon arrival at home, and at the end of the week they were instructed to return the journal. For remote measurement, five days of data is considered to be sufficient to obtain a reliable representation of a MWU's typical physical activity [29]. The qualitative data from the journal provided contextual information about the participants' experiences, complementing the qualitative GPS data. The participants were instructed to document the following entries and questions for each day: Date, Start Time, End Time, Locations Visited, Activity, How do you feel about your ability to participate in activities? Were you interacting with anyone? How did you get there? Did you encounter any barriers? How were you able to overcome those barriers? Comments or Observations.

2.2.5. GPS and Heart Rate Data

Participants were provided with a Garmin Forerunner 735XT GPS watch (Garmin Ltd., Olathe, KS, USA) (see Figure 1B). They were instructed to wear the Garmin watch and activate its recording function as soon as they left home and keep it active until they returned back home. Participants were also contacted mid-week of the study to ensure that the at-home portion of the trial was going well and that the participants were properly using the provided watch. Participants recorded their location when traveling outside of the home as well as their heart rate using the Garmin watch and saved the data every day. Upon return, the watch was connected to the Garmin Connect app via Bluetooth and the data was downloaded to a personal computer.

2.3. Data Processing

Data processing was performed using custom algorithms in Matlab software version R2023b (MathWorks Inc., Natick, MA, USA). The following sections specify as to how the different parameters used for assessing mobility and participation in the community were calculated.

2.3.1. Isokinetic Arm Strength Testing Analysis

The measured torques were analyzed to assess the arm strength of the following muscles: shoulder and elbow flexors, extensors, shoulder internal and external rotators, and shoulder abductors and adductors. The max peak torque and the mean peak torque of the test repetitions were computed and used for statistical analysis.

2.3.2. Questionnaire Analysis

The WheelCon and the LSA scores were summed up to assess the scale of the participants' self-reported confidence in wheelchair use and their extent of community participation. Scores were compiled and combined for statistical analysis.

2.3.3. 6MPT Analysis

The following parameters, including laps completed, distance, cadence, speed, and heart rate from the 6MPT were analyzed as previously described and used for further statistical analysis and comparison [28]. The inertial measurement unit (IMU) on the wrist was used to calculate the cadence, and the IMU on the wheelchair to detect turns during the test.

2.3.4. Activity Journal Analysis

The journal entries were manually analyzed for the participation of the participants in the community via the recorded visit frequency, activities, interactions, and typical barriers that impede mobility from the journal.

2.3.5. GPS and Heart Rate Analysis

The geographical representation of the recorded GPS points was mapped using the latitude and longitude functions in MATLAB. This visualization provided simple insight into the mobility pattern of the participants and their activity in the community. The velocity of the participants was calculated based on the distance between measured GPS locations and the time intervals between them. This calculation provided a continuous profile of velocity values throughout the recorded journey, allowing for a detailed examination of the mobility speed variations.

A threshold of 9 m/s was applied to differentiate between self-propelled wheeling and driving. The threshold was selected to identify all data points where the participant was moving beyond the maximum wheeling speed of a MWU [30]. Speed exceeding this threshold was categorized as driving and speed below this threshold was categorized as self-propelled wheeling. The GPS points were compared with the participants' activity journal entries and the GPS mapping to refine the classification between self-propelled and driving. This comparison helped in cases of ambiguity where slower speeds were recorded, and it was unclear from the GPS mapping whether the participant was self-wheeling or driving. The journal entries were consulted to clarify the context of specific periods. For instance, when the GPS recorded the participant visiting an open mall location at a slow pace, cross-referencing with the journal revealed activities such as drive-through banking which provided the justification to mark the segment as driving. The recorded mean heart rate was calculated for each recorded trip to investigate its relationship with speed and recorded activities from the activity journal.

2.4. Statistical Analysis

All statistical analyses were performed using SPSS software (version 28, SPSS Inc., 235 Chicago, IL, USA). The descriptive statistics were calculated across all participants. The measurement variables were assessed for normality using the Shapiro–Wilk test. To reduce the data and combine the left and right side of the torque values from the isokinetic testing, a paired *t*-test was performed and revealed no significant differences in the peak torque between the left and right arm for all recorded muscle movements ($p > 0.05$). Therefore, the mean peak torque of both arms was calculated to represent the overall upper limb strength [31,32]. Bivariate correlation using the Pearson correlation test was performed with the measured variables of the GPS data, journal, questionnaire, and isokinetic testing to determine if there is a relationship between the measured variables. Statistical significance was determined using the significance of a *p*-value less than 0.05 and a correlation coefficient greater than 0.7, indicating a strong correlation following existing guidelines and related research [33,34].

3. Results

Descriptive statistics of all ten participants for the muscle isokinetic strength testing and the 6MPT are presented in Tables 3 and 4, respectively.

Table 3. Descriptive statistics of the upper limb strength. SD—standard deviation of the mean, Flex/Ext—flexion/extension, ABD—abduction/adduction, INT—internal/external rotation.

Variable	Testing Speed (°/s)	Mean (Nm)	SD	Min (Nm)	Max (Nm)
Elbow Flex/Ext Max Peak Torque	60	59.85	14.19	38.60	80.07
	120	51.93	10.12	37.90	65.00
Elbow Flex/Ext Mean Peak Torque	60	47.34	12.97	32.17	76.22
	120	41.39	8.33	30.26	51.39
Shoulder Flex/Ext Max Peak Torque	60	79.89	21.44	41.70	123.05
	120	77.64	12.94	54.30	100.30
Shoulder Flex/Ext Mean Peak Torque	60	62.72	15.93	32.88	85.85
	120	61.53	9.37	40.28	72.33
Shoulder ABD Max Peak Torque	60	80.79	15.49	46.80	98.75
	120	85.62	16.16	66.10	106.35
Shoulder ABD Mean Peak Torque	60	61.89	11.99	37.99	77.22
	120	67.33	14.00	48.76	93.38
Shoulder INT Max Peak Torque	60	50.54	14.39	27.80	71.45
	120	51.11	13.19	33.60	70.25
Shoulder INT Mean Peak Torque	60	38.67	8.85	23.83	48.89
	120	38.28	8.41	25.11	49.21

Table 4. Descriptive statistics of the 6MPT data. HR—heart rate.

Variable	Mean	SD	Min	Max
Laps	24.60	4.12	17	29
Distance (m)	794.00	130.82	557	955
Cadence (cycles/min)	57.69	12.73	32.3	80.3
Mean Speed (m/s)	2.21	0.36	1.55	2.65
Mean HR (bpm)	121.06	17.94	98.6	150.5
Max HR (bpm)	153.44	19.08	112	179
Final Mean HR (bpm)	135.511	26.96	84.1	170.9

No GPS or activity journal data for participant 10 were collected as they did not complete the at-home portion of the trial. The mean number of locations visited by every participant as reported in their activity journal, as well as the mean number of hours they spent outside of the home, is shown in Figure 2. According to their activity journal, participant 5 spent the majority of the testing period at home. A pie chart displaying the journal-recorded types of locations visited and how often they were visited by all participants can be found in Figure 3. Similarly, a bar chart of the journal-recorded interactions and barriers encountered by the participants during the trial can be found in Figure 4. The types of barriers that were reported in the journal were all physical in nature, ranging from poor conditions of pavements to some locations lacking accessibility routes.

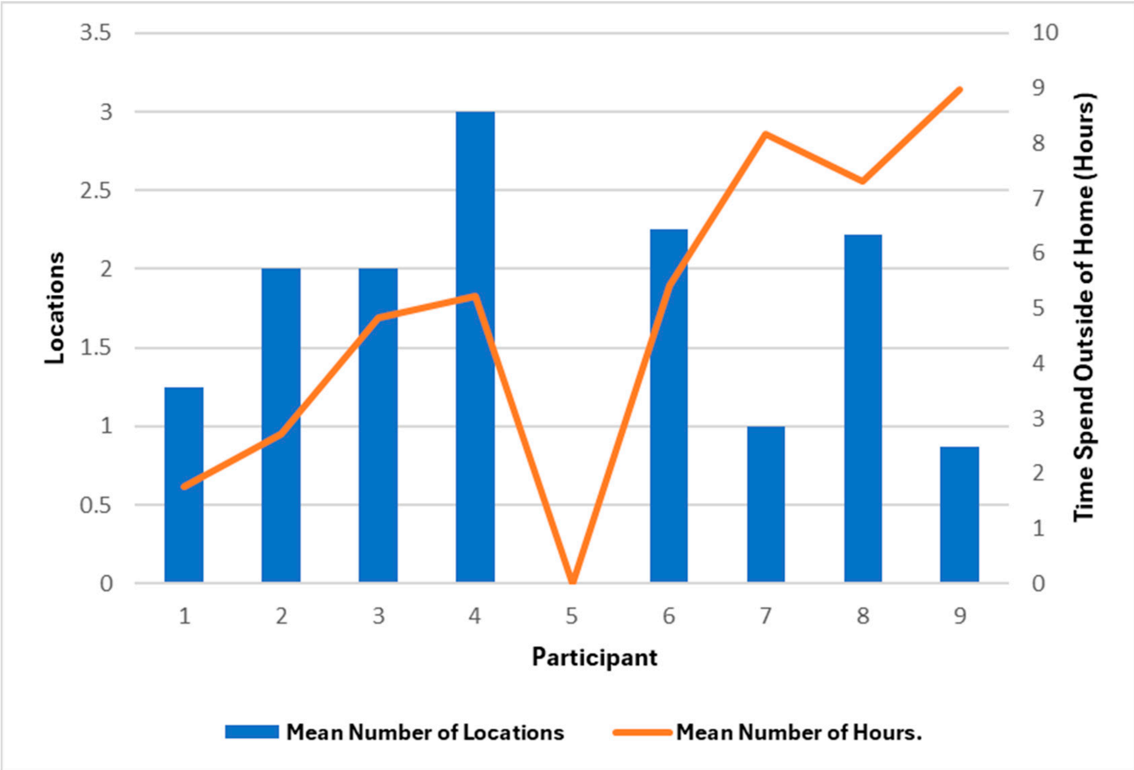

Figure 2. Mean number of locations visited, and hours spent out of the home from the journal entries.

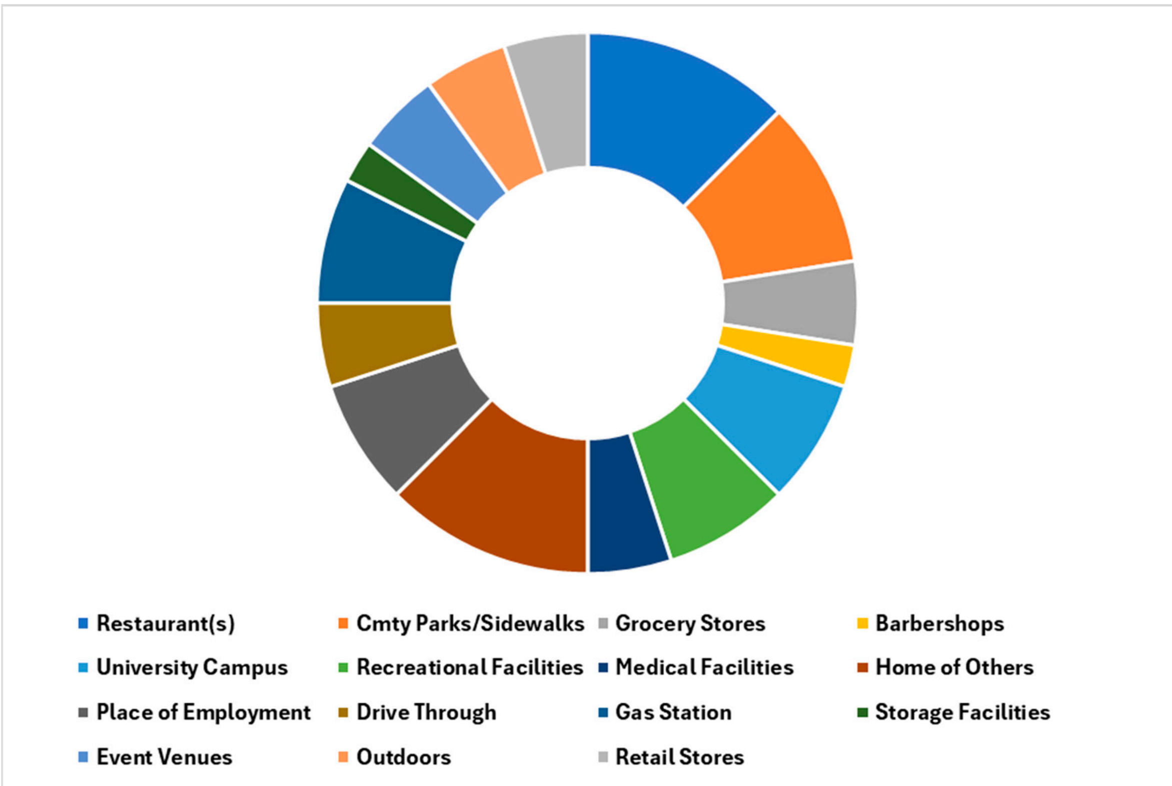

Figure 3. Types of locations visited, reported in the activity journals.

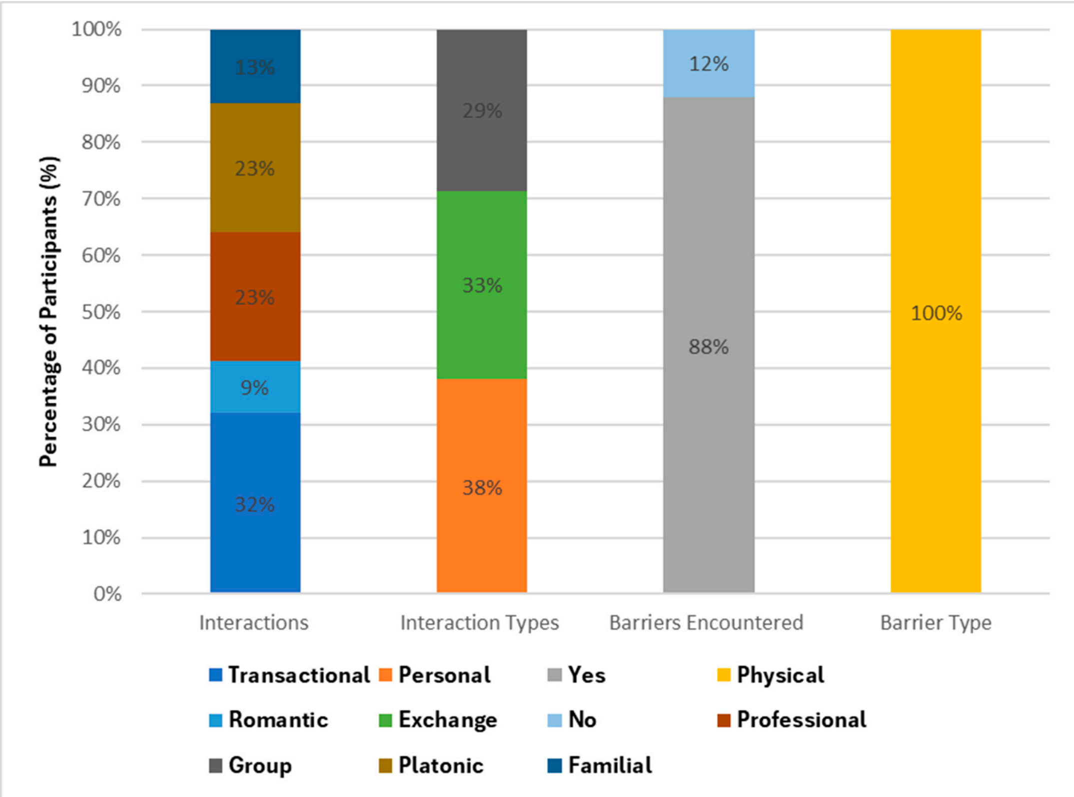

Figure 4. Data on social interactions and barriers by the percentage of participants who reported them in the activity journals.

The participants' recorded GPS data for a week is presented in Table 5 for nine of the ten participants. The table shows the total time the participants recorded their activity via the Garmin watch, how much of that was spent wheeling, the number of locations they visited during the study, and their mean heart rate during wheeling. Contrary to what they had recorded in their activity journal, the GPS recorded continuous time spent outside the home for participant 5. The GPS recorded the routes of each participant during the study, both where they went and the routes they took to get there. An example from day 2 of participant 2's recorded activity is shown in Figure 5, with the participant's heart rate and speed shown in Figure 6, while the percentage of GPS total time which was spent wheeled and the mean daily heart rate for all participants is displayed in Figure 7.

Table 5. GPS and heart rate data for 9 participants. HR—heart rate.

ID#	GPS Mean Daily Total Time (h)	GPS Mean Daily Wheeled Time (h)	GPS Mean Daily Locations Visited	Mean Daily Wheeled HR (bpm)
1	1.11	1.11	0.3	127
2	2.23	2.00	1.8	104
3	2.67	2.44	1.3	88
4	5.14	3.97	2.6	96
5	1.41	1.40	0.5	—
6	3.51	2.29	4.0	93
7	5.57	5.33	2.7	99
8	5.74	4.49	2.3	89
9	5.15	3.19	1.4	84

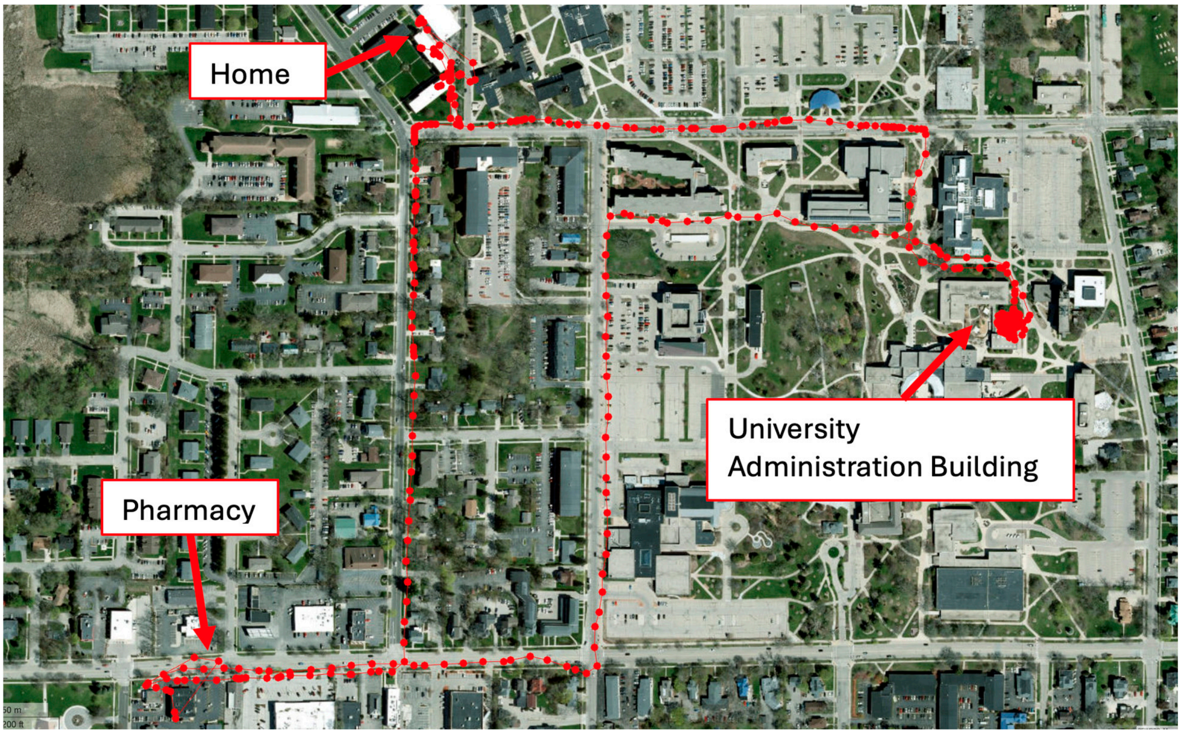

Figure 5. GPS-recorded map of participant 2's route on day 2 of the week.

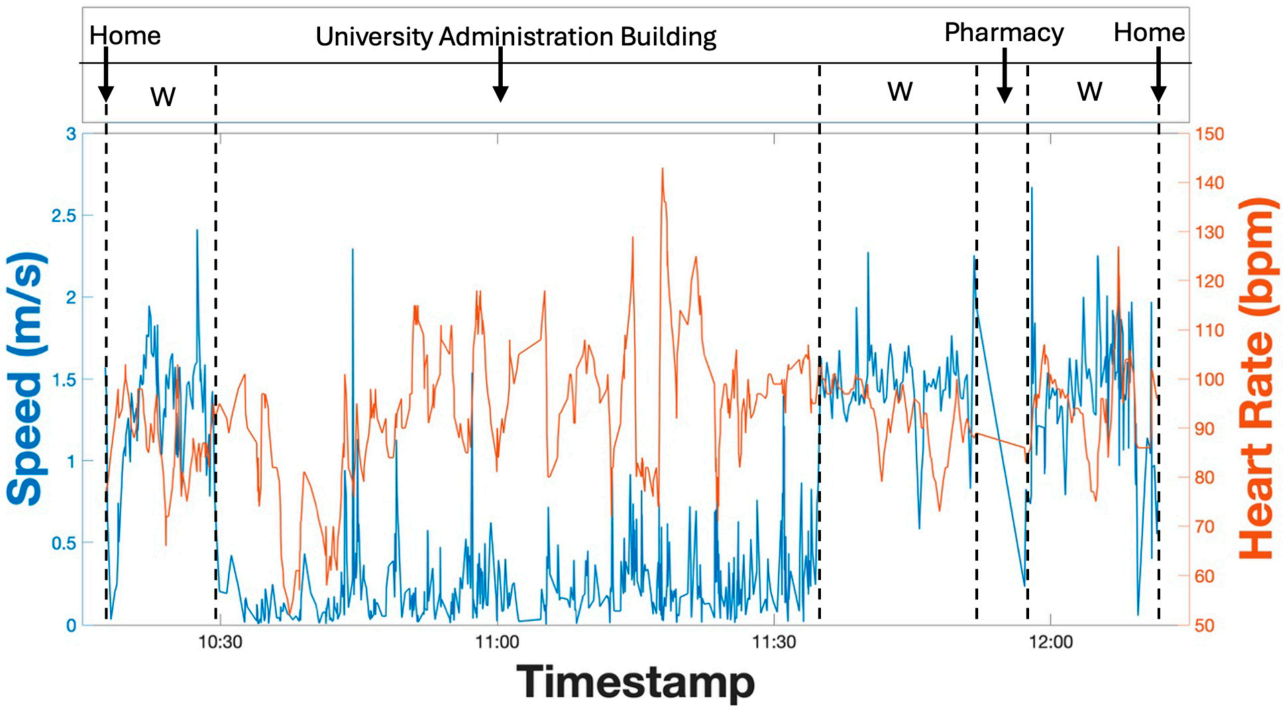

Figure 6. Sample speed and heart rate data for participant 2's wheeled route on day 2 of the week, with marked locations visited. W—Wheeled travel time.

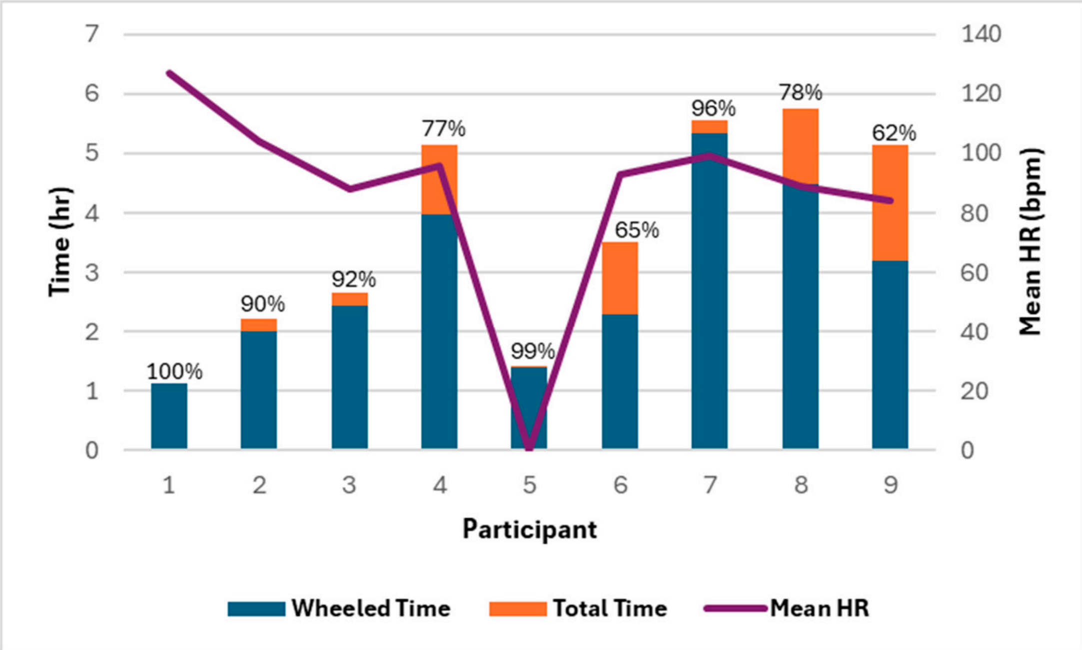

Figure 7. Total daily time spent outside the home with the percentage of daily wheeled time and mean heart rate, all recorded by the GPS watch for all participants.

Table 6 shows the result of the LSA and WheelCon scores. The WheelCon higher scores represent higher confidence in using a manual wheelchair, and for the LSA, lower scores indicate a higher level of mobility and participation. Participants with scores of (9), such as participant 8 and 9, demonstrate the highest levels of community mobility, while scores of (13), such as participants 3, 4, and 10, show the lowest levels of mobility and participation.

Table 6. Participants' LSA and WheelCon questionnaire scores.

Participant ID#	1	2	3	4	5	6	7	8	9	10
LSA Score	12	11	13	10	10	11	11	9	9	13
WheelCon Score	170	210	195	188.5	184	128	185	140	179	210
Physical	115	130	120	124	111	72	124	84	112	130
Social	55	80	75	64.5	73	56	61	56	67	80

The total WheelCon scores range from 128 to 210, and LSA scores from 9 to 13 across participants. Participants 2 and 10 have the highest WheelCon scores (210), indicating the highest levels of confidence. Participant 6 has the lowest WheelCon score (128), indicating the lowest confidence in using a manual wheelchair.

Table 7 lists the Pearson correlation analysis results from the testing between the strength measurements, the 6MPT, GPS, heart rate, journal, and questionnaire variables. The journal-recorded time outside of the home was found to have a significant, strong, positive correlation with the GPS-recorded wheeled time (r = 0.782, p = 0.022), and a significant, strong, negative correlation with the mean daily heart rate (r = −0.750, p = 0.032) as well as the mean peak torque during elbow flexion/extension at 120°/s (r = −0.736, p = 0.037).

The GPS-recorded mean daily locations visited was found to have a significant, strong, negative correlation with the mean peak torque measured during elbow flexion/extension at 120°/s (r = −0.733, p = 0.025) in addition to the maximum peak torque measured during shoulder flexion/extension (r = −0.704, p = 0.034) and the shoulder abduction/adduction (r = −0.807, p = 0.009) at 60°/s.

Table 7. Summary table of significant correlations between pairs of variables. HR—heart rate, Flex/Ext—flexion/extension, ABD—abduction/adduction, INT—internal/external rotation.

Variables		Correlation	*p*-Value
Journal Time Outside Home	GPS Wheeled Time	0.782 *	0.022
	Mean Daily HR	−0.750 *	0.032
	Elbow Flex/Ext Mean Peak Torque (120°/s)	−0.736 *	0.037
GPS Mean Daily Locations	Elbow Flex/Ext Mean Peak Torque (120°/s)	−0.733 *	0.025
	Shoulder Flex/Ext Max Peak Torque (60°/s)	−0.704 *	0.034
	Shoulder ABD Max Peak Torque (60°/s)	−0.807 *	0.009
Mean Daily HR	Shoulder Flex/Ext Max Peak Torque (60°/s)	0.808 *	0.015
	Shoulder Flex/Ext Max Peak Torque (120°/s)	0.732	0.039
	6MPT Mean HR (bpm)	0.820 *	0.013
WheelCon Physical Score	6MPT Final Mean HR (bpm)	0.756 *	0.018
	6MPT Mean HR (bpm)	0.708 *	0.033
6MPT Mean HR	Shoulder Flex/Ext Max Peak Torque (60°/s)	0.835 **	0.005
	Shoulder Flex/Ext Mean Peak Torque (60°/s)	0.732 *	0.025
	Shoulder Flex/Ext Max Peak Torque (120°/s)	0.793 *	0.011
	Shoulder Flex/Ext Mean Peak Torque (120°/s)	0.752 *	0.020
6MPT Final Mean HR bpm	Shoulder Flex/Ext Max Peak Torque (60°/s)	0.731 *	0.025
6MPT Max HR	Shoulder Flex/Ext Max Peak Torque (60°/s)	0.837 **	0.005
	Shoulder Flex/Ext Max Peak Torque (120°/s)	0.884 **	0.002
	Shoulder Flex/Ext Mean Peak Torque (120°/s)	0.803 **	0.009

Notes: * Significance at the 0.05 level (2-tailed). ** Significance at the 0.01 level (2-tailed).

The mean daily heart rate was found to have significant, strong, positive correlations with the mean heart rate measured during the 6MPT (r = 0.820, p = 0.013), and the max peak torque measured during the shoulder flexion/extension at both 60°/s (r = 0.808, p = 0.015) and 120°/s (r = 0.732, p = 0.039).

The physical score recorded from the WheelCon questionnaire was found to have a significant, strong correlation with both the mean heart rate measured during the final minute of the 6MPT (r = 0.756, p = 0.018) and the mean heart rate from the 6MPT (r = 0.708, p = 0.033).

The mean heart rate measured during 6MPT was found to have significant, strong, positive correlations with both the max and mean peak torques measured during shoulder flexion/extension at 60°/s (0.732 > r > 0.835, 0.005 < p < 0.025) and 120°/s (0.752 < r < 0.793, 0.011 < p < 0.020). Similarly, the heart rate measured during the final minute of the 6MPT was found to have a significant, strong, positive correlation with the max peak torque measured during the shoulder flexion/extension at 60°/s (r = 0.731, p = 0.025). Finally, the max heart rate from the 6MPT was found to have significant, strong, positive correlations with the max peak torque measured during the should flexion/extension at both 60°/s (r = 0.837, p = 0.005) and 120°/s (r = 0.884, p = 0.002) as well as the mean peak torque during the shoulder flexion/extension at 120°/s (r = 0.803, p = 0.009).

All other correlations were not found to be significant and are therefore not reported here.

4. Discussion

Through the combination of GPS and heart rate sensors, activity journals, questionnaires, as well as in-clinic strength and mobility assessments, this study aimed to show the viability and effectiveness of combining typical measurement methods for CMP. The correlation analysis reveals several important insights into the relationship between mobility, cardiovascular performance, and upper limb strength in MWUs. There is a strong correlation between the time participants recorded spending time outside their home and GPS-indicated wheeled time (r = 0.782, p = 0.022). This suggests that participants' self-reported data is consistent with objective GPS measurements. It also suggests that the more time the participants reported being outside on their journal, the more time they were actively wheeling themselves, indicating more physical activity, a higher level of community mobility, better physical health, and a higher quality of life.

The negative correlation found between journal-reported time outside the home and mean daily heart rate (r = −0.750, p = 0.032) suggests that higher mobility is associated with lower mean daily heart rate. Figure 7 supports this correlation, showing that participants who spend more time outside home had lower average heart rates. This could be due to several reasons. More time spent outside home could mean more commute time or more rest time at locations outside home, which could have lowered the average heart rate. It is also possible that a better level of cardiovascular fitness results from more time spent outside, which aligns with research showing that increased physical activity can improve cardiovascular health [35].

Shoulder flexion/extension and abduction/adduction peak torques at different speeds (60°/s and 120°/s) show varying degrees of correlation with the other mobility metrics examined in this study. For example, shoulder flexion/extension max peak torque at 60°/s correlates negatively with GPS daily locations (r = −0.704, p = 0.034), and positively with 6MPT mean heart rate (r = 0.835, p = 0.005), pointing to the complex interplay between muscle strength and mobility patterns, but showing that a relationship does exist between in-clinic strength assessments, in-clinic mobility assessments, and real-world community participation.

The mean heart rate recorded during the 6MPT shows strong correlations with several upper limb strength measurements. For instance, shoulder flexion/extension max peak torques at 60°/s correlates strongly with the 6MPT mean heart rate (r = 0.835, p = 0.005) and the mean heart rate measured during the final minute of the 6MPT (r = 0.731, p = 0.025). This points to shoulder flexion/extension strength having a close relationship with the cardiovascular fitness of MWUs. Additionally, these results agree with and strengthen the findings of other studies which have examined the role of upper limb strength in effective wheelchair propulsion [36–38].

The questionnaires from the WheelCon physical score correlates positively with 6MPT heart rate metrics, suggesting that a higher reported confidence in wheelchair use can provide an indicator of the cardiovascular fitness of a MWU ($0.708 > r > 0.756$, $0.018 < p < 0.033$). Participants with lower LSA scores (indicating higher mobility) generally have higher WheelCon scores. For instance, participant 2 had an LSA score of (11) and a WheelCon score of (210), suggesting a high level of mobility and confidence. Conversely, those with higher LSA scores (indicating lower mobility) often have lower WheelCon scores. Participant 6, with an LSA score of (11) and a WheelCon score of (128), exemplifies lower mobility and confidence. The analysis shows a clear relationship between community mobility (LSA scores) and wheelchair confidence (WheelCon scores). This relationship underscores the importance of both physical mobility and psychological confidence in achieving greater community participation. The findings align with previous research indicating that confidence in mobility aids, such as wheelchairs, is crucial for independent living and active participation in daily activities [3,4].

The qualitative data from the journals provided contextual information about the participants' experiences, complementing the quantitative GPS data. This approach offered a nuanced understanding of how environmental and social factors influenced the CMP of the participants during the study, which would have been missed otherwise. As seen in Figure 3, the journal records where the participant went and what activities they participated in. These records provide invaluable context to other recorded data from the GPS, clarifying the number and type of locations visited when the recorded daily routes entered areas such as enclosed malls where GPS signal was poor. The journal also gave insights into the participants' social circle as well as how often they interact with the people in their life, as seen in Figure 4. These insights provide examples and vital context to go alongside the WheelCon social confidence scores recorded from the questionnaire. Finally, the journal highlighted the environmental barriers that the participants faced during the trial which could have an impact on their CMP. The barriers that were reported were overwhelmingly physical barriers, such as poor pavement conditions and lack of accessible routes. These barriers can have a significant impact on CMP and align with our previously established international classification of functioning, disability and health model of factors affecting CMP for MWUs [2], and should not be ignored when assessing MWUs.

This study has some limitations that should be considered when interpreting the results. Firstly, the sample size is relatively small. Replicating this study with a larger sample size could help improve the generalizability of this study's findings. Larger studies could also explore the variability in responses among different demographic groups, geographical locations, and distinctions between rural and urban environments. Another limitation is the potential loss of GPS and heart rate data. This could arise from technical issues like an uncharged battery or signal loss in certain environments like densely built-up outdoor areas or indoor areas, which could have resulted in incomplete or inaccurate location and heart rate data. Future research could incorporate a redundant system that combines GPS with other technology like inertial measurement units to improve data coverage reliability in environments where GPS signals are weak or unavailable. Integrating advanced technologies like mobile health applications can enhance the precision of data collection and offer real-time monitoring of mobility patterns in the community.

This study leverages the strength of GPS technology in objectively quantifying mobility patterns such as distance traveled and frequency of community outings. This allows for detailed mapping of real-world movement, highlighting the accessibility and navigability of different environments of MWUs. The activity journal and the questionnaires complement this by providing a qualitative insight into the types of activities engaged in, the contexts of these activities, and the personal experiences and barriers faced by MWUs. With the use of the background data from the dynamometer strength testing and the 6MPT performance, this combination ensures a balanced analysis where the quantitative mobility data is enriched by the qualitative participation data providing a nuanced understanding of both the physical movement and social engagement of MWUs. It has the potential to provide the capability to better understand an individual's mobility and participation, which could help healthcare providers tailor rehabilitation programs to meet their specific needs and goals [2,5,39].

5. Conclusions

Assessing CMP is essential for setting effective rehabilitation goals for MWUs. It allows for personalized and effective rehabilitation planning, monitoring progress, enhancing quality of life, promoting social inclusion, and supporting long-term health outcomes. By combining GPS mobility tracking, heart rate, and activity journals to capture a holistic view of MWUs' mobility and participation in their daily environment, our study enables a robust and comprehensive analysis that not only quantifies the extent and nature of community mobility but also contextualizes it within the lived experiences of MWUs. Our approach enabled our study to find multiple strong correlations between variables from the GPS, 6MPT, isokinetic dynamometer, and questionnaires. These findings point to relationships between in-clinic measurements and real-world metrics which, to our knowledge, has not been shown in previous research. This approach facilitates more targeted and effective rehabilitation strategies that can address physical capabilities, psychological components, and environmental barriers associated with the CMP of MWUs.

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