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case report

Objective Functional Assessment After a Head Injury Using Movement and Activity in Physical Space Scores: A Case Report

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Objective: To describe the potential benefit of using a global positioning system (GPS) and accelerometry as an objective functional-activity measure after concussion by creating Movement and Activity in Physical Space (MAPS) scores.

Background: A 21-year-old female soccer player suffered a blow to the back of the head from an opponent's shoulder during an away match. No athletic trainer was present. She played the remainder of the match and reported to the athletic training facility the next day for evaluation.

Differential Diagnosis: Concussion.

Treatment: The athlete was removed from all athletic activities. Her symptoms were monitored based on the Zurich guidelines. She was also instructed to wear an accelerometer on her hip and to carry an on-person GPS receiver at all times for 10 days. Her total symptom scores for the 4 symptomatic days were 82, 39, 49, and 36. Her mean MAPS functional score for symptomatic days 3 through 5 was 900.9 and for asymptomatic days 6 through 11 was 2734.9.

Uniqueness: We monitored the patient's function during the concussion-recovery process using an on-person GPS receiver and accelerometer to calculate personalized MAPS scores. This novel approach to measuring function after injury may provide a useful complementary tool to help with return-to-play decisions.

Conclusions: An on-person GPS receiver and accelerometer were used to observe the patient's physical activity in a free-living environment, allowing for an objective measure of function during recovery. Her MAPS scores were low while she was symptomatic and increased as she became asymptomatic. We saw the expected inverse relationship between symptoms and function. In situations where accuracy of reported symptoms may be a concern, this measure may provide a way to verify the validity of, or raise doubts about, self-reported symptoms.

Key Words: concussions, global positioning system, geographic information systems, accelerometer, functional outcome measures

An estimated 1.6 to 3.8 million concussions occur in the United States annually as a result of sports participation, accounting for 4.4% to 5.6% of all injuries in high school and college football and 7% of hockey-related emergency room visits.[1–3] A *concussion* is a biomechanically induced transient disturbance of neurologic function.[4] Common signs and symptoms of concussion include headache, dizziness, mental confusion, disorientation, blurred vision, and balance impairments.[2,5]

Concussions are complex to assess, which makes tracking recovery difficult. Currently, few data-derived standards for concussion assessment are accepted.[2] Frequent concussion-assessment methods are symptom scales, neurologic screening, sideline memory and concentration screening, balance assessment, and neuropsychological testing. The most recent assessment trends showed that more than 85% of athletic trainers (ATs) rely on clinical examination, symptom checklists, and return-to-play guidelines; only 48% reported using the Standardized Assessment of Concussion (SAC), 18% used neuropsychological testing, and 16% used the Balance Error Scoring System (BESS).[6] These tools help identify the effects of a concussion by evaluating symptoms and cognitive and balance impairments; however, they do not address patient function during the recovery process. Understanding patient function may help to improve return-to-play decisions after concussion by providing objective data.

The Movement and Activity in Physical Space (MAPS) System was developed to objectively measure patient function in the free-living environment. The MAPS system is designed to evaluate continuous accelerometer data (steps and physical activity counts), precise location data (from global positioning system [GPS] records), and travelogues (self-recorded) to create a detailed picture of function. It collects 14 activity-environment–related variables, including minutes away from home and activity counts per location. The use of these technologies is not part of the standard concussion-assessment protocol but was added based on the success we had with patients after knee surgery.[7] This method allows the environmental factors associated with concussions to be assessed objectively. The data resulting from these devices are processed to produce 2 MAPS scores, which are quantitative measures of patient function. Both MAPS intensity ($MAPS_I$) and MAPS volume ($MAPS_V$) scores were validated as measures of function in postsurgical knee patients and people with multiple sclerosis.[7,8] The principle behind the MAPS system is that a patient suffering from an injury will be less likely to participate in normal daily activities. This decrease in activity and participation will be demonstrated with lower MAPS scores, indicating a lower level of function. Using MAPS scores as an objective measure of function may provide ATs with a more detailed assessment of function

Figure 1. An individual wears the accelerometer on the right hip and the global positioning unit inside a small cell phone case (for enhanced portability).

after injury. The purpose of this case report is to highlight the use of an objective functional measure, MAPS scores, to monitor recovery after concussion.

CLINICAL PRESENTATION

A 21-year-old National Collegiate Athletic Association Division III women's soccer midfielder suffered a blow to the back of the head from an opponent's shoulder while participating in an away match. No AT was present to immediately diagnose the injury. The patient reported to the athletic training facility the following day and was assessed by an AT, who performed a detailed evaluation. Once a concussion was identified, the Sport Concussion Assessment Tool 2 (SCAT2) was administered. The SCAT2 combines aspects of several concussion tools into 8 components to assess concussion symptoms, cognition, and neurologic signs.[9] The SCAT2 includes a 22-item graded symptom scale, the SAC, a modified Maddocks questionnaire, the Glasgow Coma Scale, assessment of physical signs, a modified BESS, and an examination of coordination. The last component of the SCAT2 is the delayed-memory section of the Standardized Assessment of Concussion.

At the evaluation, the patient reported headache, "pressure in the head," dizziness, confusion, not "feeling right," light sensitivity, feeling "slowed down," difficulty concentrating and remembering, fatigue, drowsiness, and being emotional. She demonstrated a 31-point decrease from her baseline score on the SCAT2. Although the SCAT2 was recommended by the 3rd International Conference on Concussion in Sport held in Zurich,[10] limited normative data are available for the tool,[11,12] and no guidelines indicate the amount of a decrease that reflects a significant change from baseline to postinjury performance. A thorough head and cervical spine examination were otherwise unremarkable. Vital signs and cranial nerve function were within normal limits.

PROTOCOL AND NOVEL FUNCTIONAL ASSESSMENT

The patient was instructed to rest and refrain from practice and other activities, in accordance with the Zurich concussion guidelines,[10] until her symptoms resolved. During this time, she was given an accelerometer to wear on her pants on her right hip (over the anterior-superior iliac spine) at all times except for sleeping and grooming, as well as a GPS unit to carry while out of the house. The GPS unit was placed in a small cell phone case for easier portability. An individual (not the patient) is shown wearing the 2 devices in Figure 1. The patient wore the devices for 10 days, beginning the day after her concussion was diagnosed. To enhance the validity of the location measures, she was asked to complete travelogues of time spent at locations, activity while at locations, and travel times. During this 10-day period, the patient's symptoms were recorded daily using a symptom scale based upon the theory of unpleasant symptoms.[13] The scale is a 22-item survey that identifies each symptom and measures 3 components of each symptom (severity, frequency, and bothersomeness). The scores for the 3 components are added to obtain a total symptom score. The SCAT2 was used initially but not administered while the athlete was symptomatic.

We used an accelerometer (model GT3X+; Actigraph, LLC, Pensacola, FL) to continuously measure free-living physical activity. The GT3X+ is a triaxial accelerometer (measuring 4.6 × 3.3 × 1.5 cm and weighing 19 g) that quantifies and stores physical activity information and outputs data in user-defined epoch lengths. Data are downloaded using the Actigraph software and stored in a computer database. An important feature of the data is that they are time stamped, which allows activity to be matched to known GPS-identified locations.

We used the Tracking Key Pro (measuring 7.6 × 5.0 × 3.6 cm and weighing 158 g) GPS receiver (LandAirSea Systems Inc, Chicago, IL) to record athlete longitude, latitude, and speed and to determine the mode of transportation. The GPS unit can log tracks (up to 100 hours), which can then be used to infer instantaneous speed, trip distance, and trip time. The receiver uses up to 16 satellites to track the individual. The manufacturer reports an accuracy of approximately 3 m under ideal sky conditions; however, the accuracy can be substantially degraded by various atmospheric and ground conditions. The GPS units used in this study had been used previously to successfully identify the location and travel of postsurgical knee patients without any significant accuracy problems due to atmospheric and ground conditions.[7,14]

Movement and Activity in Physical Space Score Formula

The MAPS score is a new unit of measure combining multiple types of data to quantify function in free-living space. It reflects activity scores by locations away from home, normalized by time spent at locations, summed for each day, and then averaged over 3 to 5 days. The formula for MAPS is expressed as

$$\text{MAPS score} = \frac{\sum_{T=1}^{m}\left[\sum_{L=1}^{n}\left(\frac{A_L}{t_L}\right)\right]}{T}$$

where t_L is the time spent at a location other than home (determined from GPS and travelogue analysis), A_L is a measure of activity (from accelerometer readings) at that

Table. Patient's Movement and Activity in Physical Space (MAPS) and Symptom Scores

Days Postinjury, No.[c]	Outcome Measures[a]		Symptom Scores[b]			
	$MAPS_I$	$MAPS_V$	Severity	Frequency	Bothersomeness	Total
2	83.6[d]	2.8[d]	28	21	33	82
3	865.2	24.4	14	12	13	39
4	815.4	23.5	16	15	18	49
5	1022.1	24.8	12	12	12	36
6	206.0[e]	4.5[e]	0	0	0	0
7	1013.8	29.1	0	0	0	0
8	4601.7	76.1	0	0	0	0
9	2856.1	66.1	0	0	0	0
10	3291.3	84.6	0	0	0	0
11	4440.5	87.7	0	0	0	0

Abbreviation: $MAPS_I$ indicates MAPS intensity; $MAPS_V$, MAPS volume.

[a] See text for equation.

[b] Based on a 22-item survey that identifies each symptom and measures its severity, frequency, and bothersomeness. Scores for the 3 components are summed for the total score. The patient's symptom scores indicate her symptoms lasted 5 days postinjury.

[c] Data for day 1 were not available because the patient did not report the concussion until the day after injury.

[d] The MAPS scores for day 2 were low because the day's data were incomplete.

[e] The MAPS scores for day 6 were low because the recording day was a Sunday; the patient was very inactive on this day.

location, and T is the number of days used to average daily activity scores. Depending on whether A_L is measured in activity counts (intensity) or step counts (volume), the system yields either a $MAPS_I$ or a $MAPS_V$ score, respectively. Although physical activity is expected at home, it does not represent a person interacting with the environment. Therefore, only locations other than home are considered.

Concussion-Assessment Results

The patient became asymptomatic 6 days after the injury (fifth day of data collection) and began a gradual return-to-play protocol based upon the Zurich concussion guidelines.[10] She started with light activity that progressed to moderate and then vigorous activity and finally returned to practice 10 days after injury (ninth day of data collection), once she was cleared by a physician. This case followed a course similar to that seen in typical concussed individuals, with resolution of symptoms occurring within 3 to 7 days after injury.[15]

The novel approach is the use of MAPS scores and the tracking of function during recovery. We monitored the patient's function from the day after injury throughout the concussion-recovery process and return to sport using an accelerometer and GPS unit to calculate MAPS scores.

Measuring function after injury may provide useful complementary objective data to aid in making complex return-to-play decisions. It may also be used to help determine patient compliance with physical-activity restrictions or to possibly see if the patient is malingering. As shown in the Table, the patient's total symptom scores for the 4 symptomatic days were 82, 39, 49, and 36 (mean = 51.5). She reported a total symptom score of 0 from day 6 onward; thus, she was symptom free after the 5 days. Her daily $MAPS_I$ scores for days 2 to 5 (while symptomatic) were 83.6, 865.2, 815.4, and 1022.1. Data collection began late on day 1, producing an incomplete day of data. This can be seen in the extremely low score for day 2. Her mean $MAPS_I$ functional score while symptomatic (excluding incompletely recorded days) was 900.9, and her mean $MAPS_I$ functional score while asymptomatic was 2734.9, which represents a 3-fold increase (Figure 2). Examination of other patient populations yielded average $MAPS_I$ scores of 480.6 ± 344.0, 1314.9 ± 1632.7, and 2957.0 ± 2812.0 for postsurgical knee patients, multiple sclerosis patients, and healthy adults, respectively.[8]

The daily $MAPS_I$ and total symptom scores, which illustrate the expected inverse relationship between symptoms and function, are presented in Figure 3. As the patient's symptoms decreased, MAPS scores increased correspondingly and continued to increase after she was cleared for participation by the team physician. Another interesting observation was that on day 4, the patient reported that she "went to volleyball game!—not a good idea" and her symptom score increased. This information was documented by the patient in her travelogues and on her symptom survey. This increase in symptoms was also reflected in her daily $MAPS_I$ score, which decreased from 865 to 815. This example highlights 1 potential advantage to MAPS scores: their ability to objectively observe a patient after injury. When noncompliance is a concern, MAPS scores can provide objective data without the need to rely on the patient's self-report.

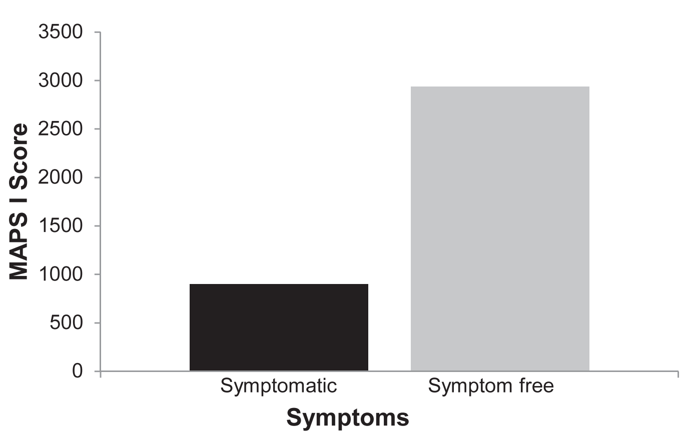

Figure 2. Average Movement and Activity in Physical Space intensity ($MAPS_I$) score for the patient while symptomatic and symptom free. Incomplete days were those with less than 10 hours of wear time and were excluded from the analysis.

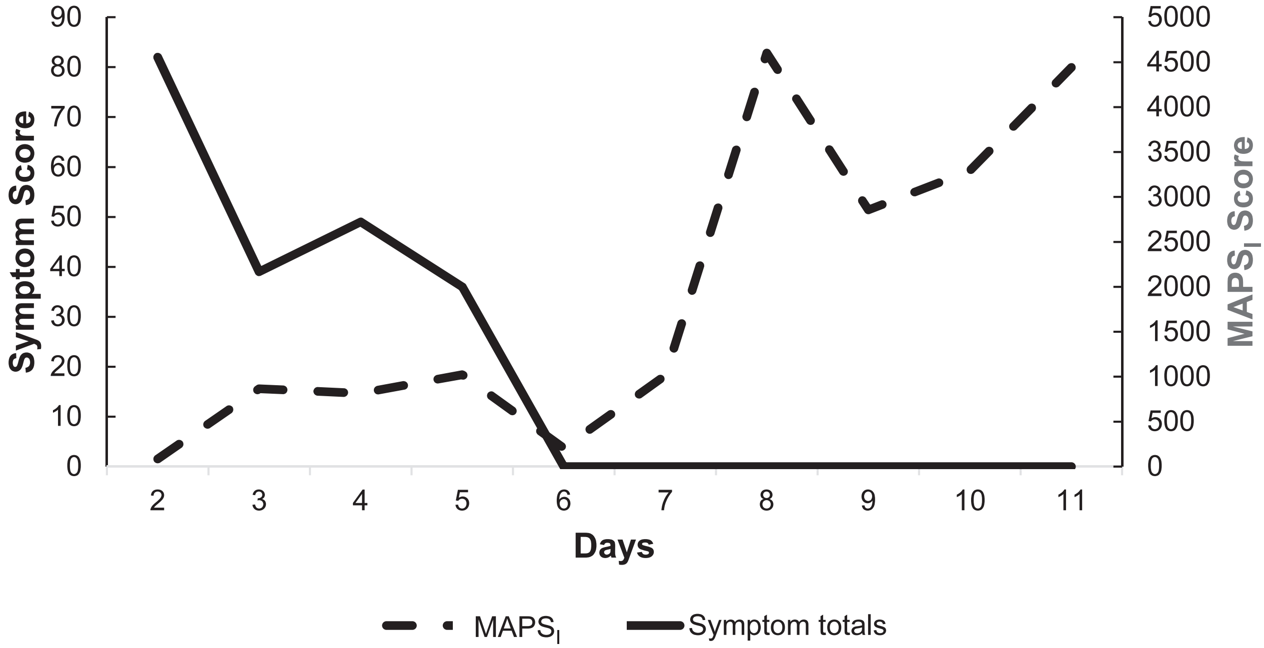

Figure 3. The relationship between Movement and Activity in Physical Space (MAPS) intensity score and the patient's symptom scores in the 10 days after sustaining the concussion.

We used the MAPS information to identify the patient's function after concussion on days 2 (first full day of data collection), 5 (last symptom day), and 10 (clearance by physician). Figure 4 shows a difference in person–environment interaction among the 3 days. This difference can be seen in a variety of ways by separating the individual components of the MAPS scores to demonstrate how variables, such as activity counts, number of locations, and time at locations, interact. First, on day 2, the patient only visited 5 locations other than home (athletic training facility twice, cafeteria, class, and library), whereas on day 10, she visited 10 locations other than home (eg, cafeteria, class, library, soccer practice). The white area represents the amount of time spent away from home: on day 10, she clearly spent more time interacting within the environment outside of the home. Day 5 also showed a small increase in the time spent away from home compared with day 2. The other noticeable difference is in the intensity of activity. After 10 days, the patient more than doubled her daily activity counts compared with day 2.

DISCUSSION

This case report followed the recovery of a concussion patient. Her symptom resolution after injury was similar to that of other cases and did not exhibit any unusual patterns. The uniqueness in this case stems from the novel approach to evaluating and observing patient function after concussion, which may reveal a more complete picture of a patient's level of function postinjury.

The MAPS system produces variables that are consistent with the World Health Organization International Classification of Function, Disability, and Health (Figure 5) definition of function. *Function* is a dynamic interaction among interrelated components, including body functions and structures, activity, participation, environmental factors, and personal factors.[16–20] This model explains that management of injuries requires a broader scope than merely impairment-based assessment, and it focuses on the components of health, rather than the consequences of disease.[17]

Body function and structures refers to the physiologic functions of body systems and the anatomical parts of the body, such as limbs, and their components. Irregularities in function and structure are referred to as *impairments*, which are defined by range-of-motion loss, muscle weakness, and pain and fatigue.[19,20] After concussion, evaluating patient impairment is strongly emphasized, particularly early in the course when activity is contraindicated. The SAC, SCAT2, neuropsychological testing, BESS, and many other concussion-screening tools evaluate a patient's cognitive and balance impairments. It is important that health care professionals evaluate the patient's overall function and do not limit themselves to 1 domain.

Activity and participation are often represented as a single component. *Activity* represents the act of completing a task and is related to a patient's perception of function. *Participation* refers to the involvement of a patient in real-world situations. Limitations in activity and participation are demonstrated in difficulties with walking, climbing steps, grasping, or carrying.[19,20]

Activity and participation is an area that has been previously lacking from concussion assessments. By including measures to assess these components, we enhance our evaluation techniques to provide a better understanding of patient function and compliance after injury. Physical activity has been used in a variety of other patient populations as an objective measure of patient function. For example, 3 months after stroke, there was a strong relationship between patient step counts and other mobility outcome instruments.[21] Patients with peripheral artery disease[22] or neurologic disease[23] displayed significantly fewer step counts than healthy matched controls. In addition, as the health of the patients with neurologic

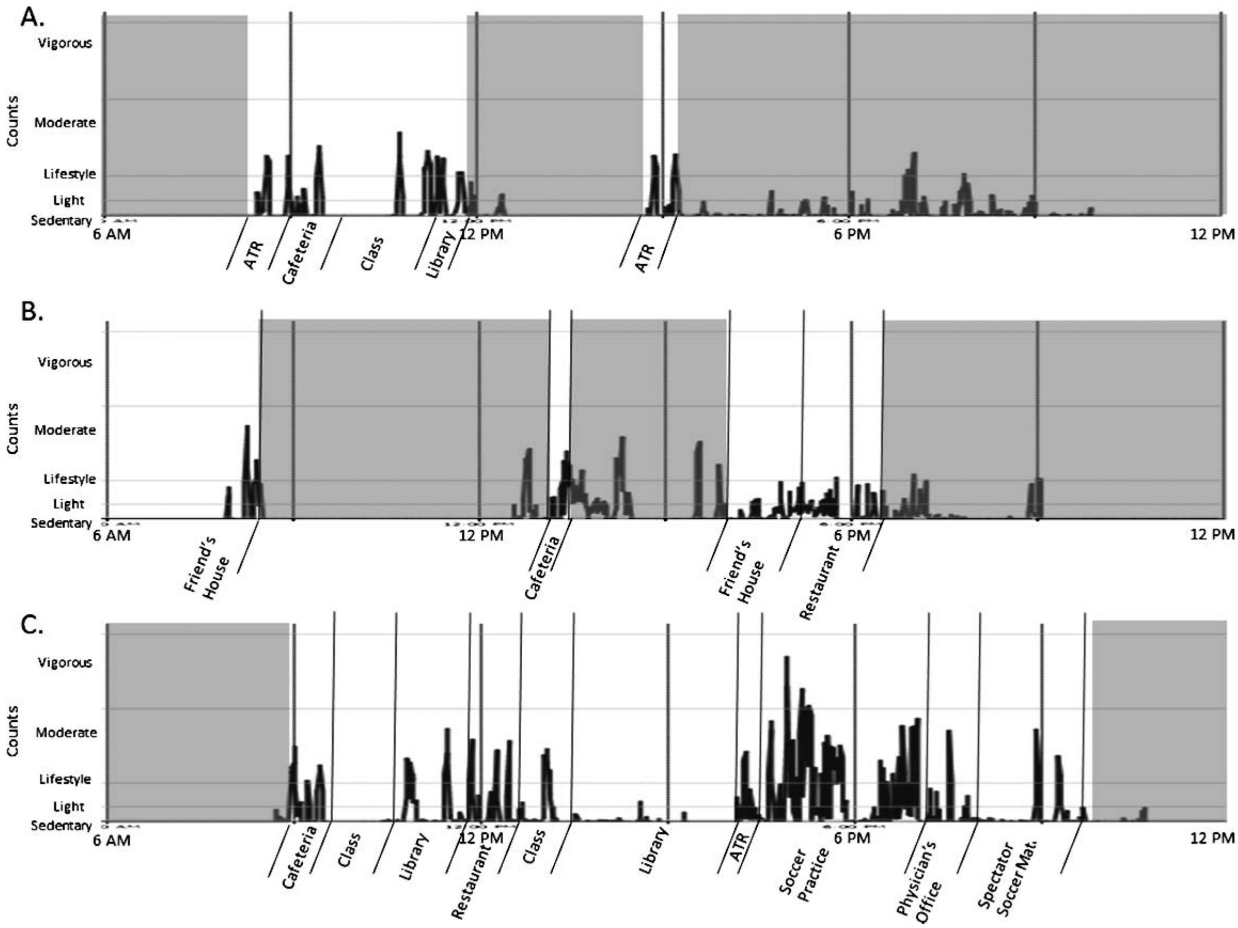

Figure 4. The patient's movement and activity in physical space after concussion. A, Day 2. B, Day 5. C, Day 10. The horizontal lines represent varying thresholds of activity intensity (eg, light, moderate).The thick black line above the x-axis represents the patient's varying activity intensity throughout the day. The gray areas represent time at home. The vertical lines separate locations. Abbreviation: ATR, athletic training room.

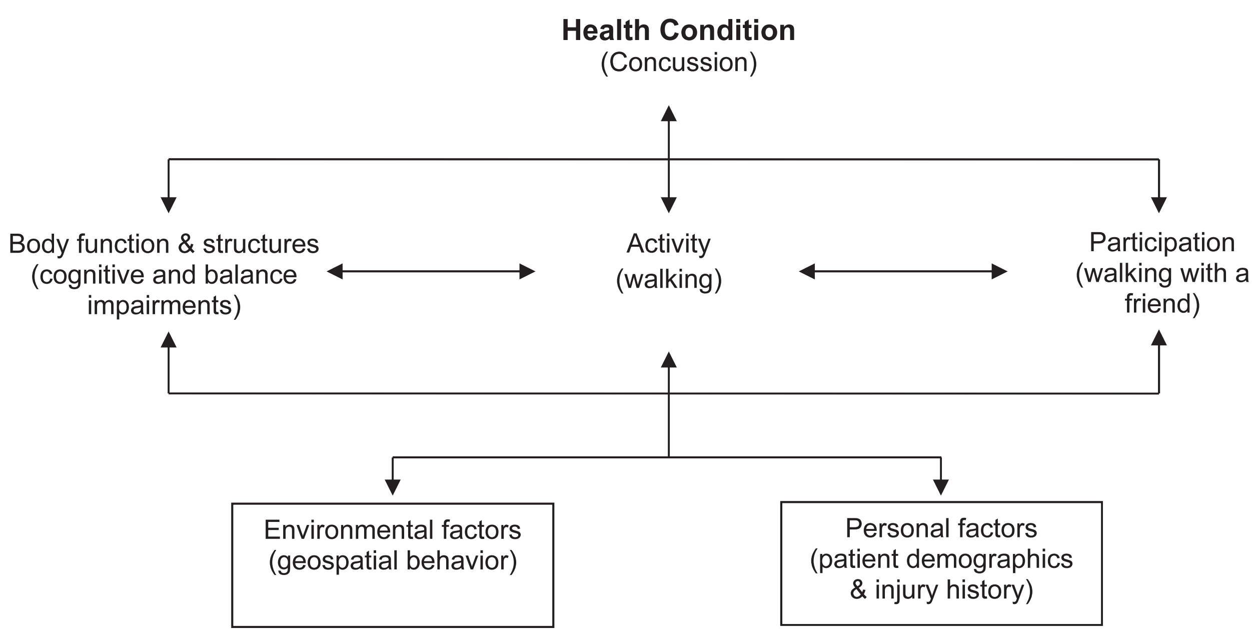

Figure 5. World Health Organization International Classification of Function, Disability, and Health model.

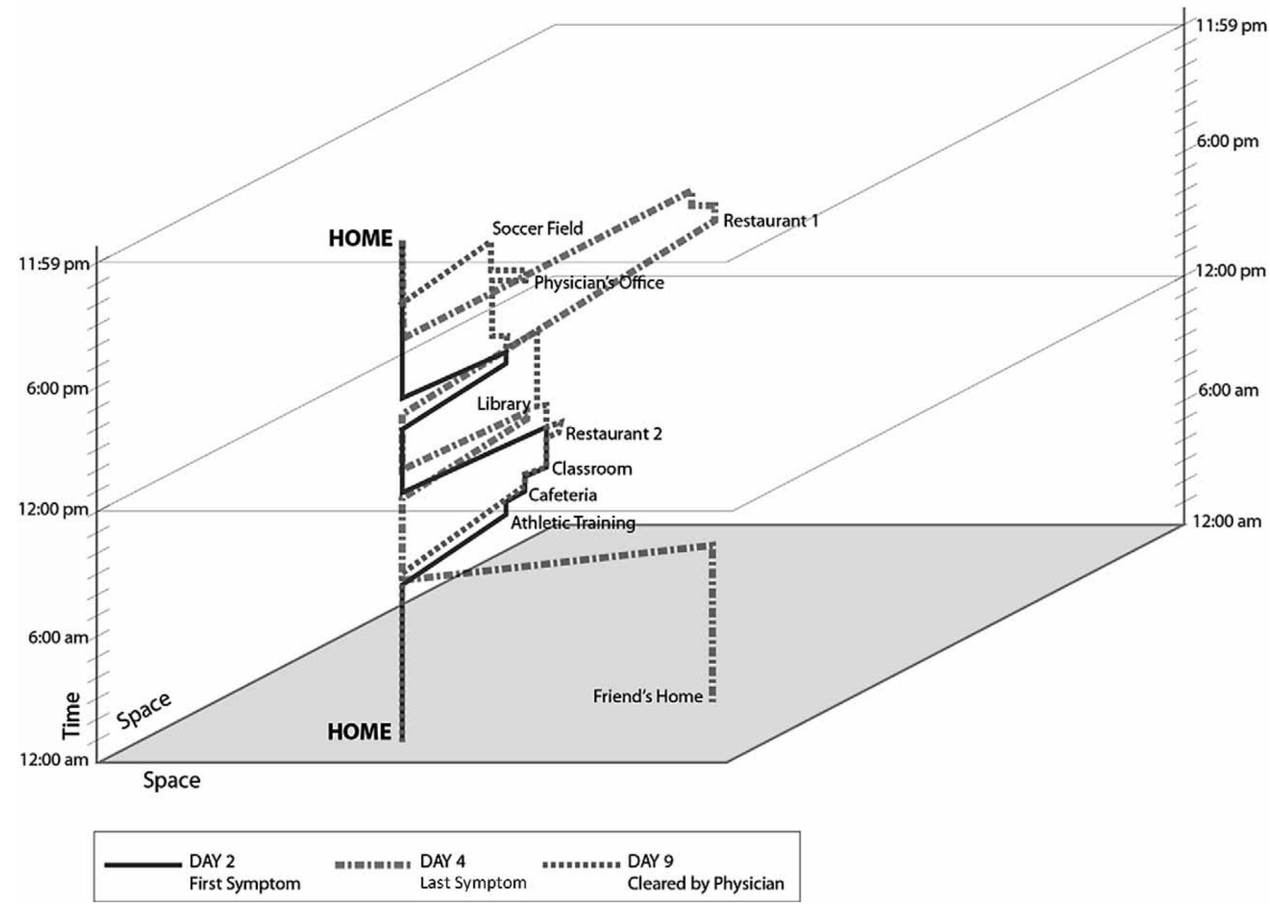

Figure 6. Schematic visualization of the patient's activities on sample days in geographic space. Each line represents a sample day's movement record in the space-time cube, which is a familiar time-geographic space for visualizing and computing with time-stamped sequences of physical-activity paths.

disease improved, so did the number of steps per day. Patients with fibromyalgia and chronic fatigue syndrome had lower activity levels than controls and spent less time performing high-intensity activities. The activity levels of these patients were inversely related to concurrent ambulatory pain and fatigue.[24] Although physical activity measures provide a crude assessment of patient function, they lack the contextual factors to identify the differences between activity and participation described by the World Health Organization International Classification of Function, Disability, and Health.

Environmental factors are external physical, social, cultural, or institutional elements that may influence a person's interaction within free-living space.[17,19,20] These external elements can influence individual function in a variety of different ways, such as distance traveled and terrain traversed. Another example is the external influence an AT has on patient function by increasing patient motivation.

Personal factors describe the internal influences on patient function. These factors include past injury history and demographic information such as age, height, weight, and personal history. A concussion may have different effects on patients with a history of multiple concussions and younger patients compared with patients having no history of concussion and older patients. It is important to note these differences in personal factors because they can determine how the injury is assessed and managed.

The dynamic interaction among these components and factors provides the AT with a broader picture of patient function. This model represents a transition from the disease-centric approach to a more comprehensive patient-centered approach to care.[20]

THE MAPS INFORMATION SYSTEM

This case study is part of a larger program to develop the MAPS system for integrating information from multiple sources about individual behavior and the geographic space that supports and shapes function, disability, and health. By developing geospatial analytical and mapping technologies, we aim to measure and view function as it occurs in geographic space. Linking activity to its geographic context is critical for the success of MAPS research. Human movement and function in geographic space are clearly influenced by several types of contextual social, economic, and environmental factors.

Today, several commercial and open-source geographic information systems (GISs) are available for managing, modeling, visualizing, and analyzing geographic information. However, most GISs focus on spatial analysis while ignoring the temporal aspects of geographic information. Physical-activity analysis requires not just static spatial representational models but dynamic spatiotemporal models that support continuous activity modeling as it occurs in geographic space. Currently, most GISs support only snapshot modeling of spatiotemporal processes through multiple spatial representations at different time intervals. Instead, integrated space-time data-modeling methods for representing continuous physical activity data in GIS databases are needed.

As an example, examine the visual schematic developed in Figure 6 to represent physical activity within a space-time cube, a popular method for modeling geographic activities and activity space in time geography. As is common for all mapping, geographic space is abstracted as a 2-dimensional plane; adding the third dimension of time creates the space-time cube representation model. An individual's movement in space can be mapped as an upward-trending line in the space-time cube. Because all physical movements imply some passage of time, movement parallel to the 2-dimensional spatial plane is impossible. In our case, for ease of visualization and comparative analysis, the time dimension is generalized to represent only the template day: thus, all daily activity charting lines are visualized contemporaneously, starting from the same 12:00 AM time plane and ending at the 11:59 PM time plane. As opposed to a conventional 2-dimensional map, this method of visualization allows us to easily compare and analyze different movement patterns that emerge by examining multiple daily activity lines simultaneously. As shown in Figure 6, on day 2, the first day of symptoms, a much larger portion of time was spent at home than on day 5 (last day of symptoms reported) or day 10 (when the physician cleared the patient). Also, the maximum distance traveled from home increased as the patient recovered. If modeled within a temporal GIS, the activity line would allow not only visual analysis but also computational detection and analysis and statistical validation of spatiotemporal patterns. Note that although we prepared the image in Figure 6 manually using graphic design software, dedicated software products would need to be developed for computational analysis and visualization. The GIS technologies offer the best support for developing such software. Some attempts have already been made, and we hope that new tools will become commonplace for geographic analysis of physical activity and function.

CONCLUSIONS

We used an on-person accelerometer and GPS receiver to observe the patient's physical activity in a free-living environment and obtain an objective measure of function during recovery. Her MAPS scores were low while she was symptomatic and increased as she became symptom free: we saw the expected inverse relationship between symptoms and function. In situations where accuracy of reported symptoms may be a concern, this measure may provide a way to verify the validity of, or raise doubts about, self-reported symptoms. Current concussion-assessment tools focus on symptoms and impairments and are largely subjective in nature. The MAPS scores present an objective way for ATs and other health care professionals to measure patient function after concussion, which may be used as part of the return-to-play decision.

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