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A Novel Sensorized Shoe System to Classify Gait Severity in Children with Cerebral Palsy

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Abstract – **The clinical management of children with Cerebral Palsy (CP) relies upon periodic assessments of changes in the severity of gait deviations in response to clinical interventions. Current clinical practice is limited to sporadic assessments in a clinical environment and hence it is limited in its ability to estimate the impact of CP-related gait deviations in real-life conditions. Frequent home-based quantitative assessments of the severity of gait deviations would be extremely useful in scheduling clinical visits and gathering feedback about the effectiveness of intervention strategies. The use of a wearable system would allow clinicians to gather information about the severity of gait deviations in the home setting. In this paper, we present ActiveGait, a novel sensorized shoe-based system for monitoring gait deviations. The ActiveGait system was used to gather data, under supervised and unsupervised conditions, from a group of 11 children with various levels of CP-related gait deviation severities. We present a methodology to derive severity measures based on features extracted from Center of Pressure (CoP) trajectories. Results show that a Random Forest classifier is able to estimate severity scores based on the Edinburgh Visual Scale with a level of accuracy >80% adequate for clinical use.**

I. Introduction

CEREBRAL palsy (CP) is a group of permanent (but not unchanging) disorders of the development of movement and posture caused by brain damage that occurs when the brain is still immature or developing during the prenatal, perinatal or postnatal periods [1]. CP is the most common cause of severe disability in the childhood, with a prevalence of 3.3 cases per 1000 in the United States [2]. CP causes activity limitations and is frequently associated with sensory and cognitive abnormalities, communication impairments, behavioral problems and seizures [1]. This disorder often leads to abnormal motor control that causes difficulties with balance, poor coordination, weakness, muscle tone abnormalities, impaired selective motor control, delayed motor milestones, and pathologic reflexes [3].

The clinical management of CP largely focuses on maintaining function, improving quality of life and preventing secondary complications [4]. Numerous approaches are available to treat spasticity and inadequate muscle function, including stretching, night splinting, serial casting, physical therapy, medication, botulinum toxin injections, and in some cases orthopedic surgeries [5]. The response of children with CP to such interventions is marked by high variability both in the magnitude of the correction of the gait abnormalities as well as in the time span during which the intervention remains effective. Continuous assessment of the severity of gait deviations would be extremely useful in scheduling clinical visits and, if needed, revising the intervention strategy. Current practice of clinical assessments only partially captures the impact of CP-related gait deviations in real-life conditions. A clinical assessment that is meant to improve mobility in children with CP would aim to impact their behavior in real-life conditions. Hence, there is a need for an objective tool to perform assessments of gait deviations in children with CP in the home and community settings.

In a previous study, we demonstrated that the severity of gait abnormalities associated with CP can be assessed via analysis of the trajectory of the center of pressure (CoP) [6]. In this paper, we present a novel sensorized shoe system called ActiveGait. Unlike commercially available systems, which are mostly designed for lab-based short-term data collections [7, 8], the ActiveGait system was specifically designed to gather gait data from children with CP in the home and community settings. Herein, we show that we can reliably estimate the severity of gait deviations using features extracted from CoP trajectories derived from the shoe system.

II. Methods

A. ActiveGait

Data collection was performed using the ActiveGait System, developed by Simbex LLC (Lebanon, NH). ActiveGait consists of an instrumented shoe with 15 insole sensors (iSole), one ankle angle sensor, a data collection unit, as well as external download hardware and data processing software. The iSole is made up of 15 force sensitive resistors positioned within a custom-made insole. 11 of the sensors are 0.5" in length, while the remaining 4 sensors are 1.5" in length. The short sensors are placed in the metatarsal region of the insole. The long sensors are placed in the heel region. Placing more sensors towards the front of

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the foot allows one to increase the accuracy of center of pressure (CoP) trajectory estimates, especially for children who show a toe-walking pattern. To calculate the CoP, we use the following formulas:

$$XCOP = \sum_{i=1}^{15} W_i * x_i * \left(\frac{F_i}{F_{tot}} \right)$$

$$YCOP = \sum_{i=1}^{15} W_i * y_i * \left(\frac{F_i}{F_{tot}} \right)$$

where XCOP is the CoP position in the mediolateral direction, YCOP is the CoP position in the anteroposterior direction, *i* is the sensor number, W is a weight factor, x is the mediolateral location of the sensor, y is the anteroposterior location of the sensor, F is the force measured by a given sensor and F_{tot} is the sum of forces measured by all sensors combined.

The ActiveGait System (figure 1) has two programmable modes: 1) Continuous Mode: In this mode, the system collects data continuously for a set period of time. The purpose of this mode is to allow clinicians to collect data in a controlled environment such as a laboratory. 2) Normal Mode: In this mode, the system collects data until the data collection is stopped. This mode was designed for longitudinal monitoring in the home setting. To conserve power, the system monitors pressure on a sensor placed under the forefoot and goes into a low-power sleep state when the pressure falls below a set threshold (e.g. when subject takes the shoe off).

Figure 1. The ActiveGait System. The picture shows the instrumented shoe together with the connections and software component of the system.

B. Data collection

We recruited a total of 11 children (age 12.6 ± 3 years old) diagnosed with CP. To be considered eligible to participate in the experimental procedures, subjects had to be able to walk at least 50 feet without assistance from another person. Assistive devices (i.e. crutches and walkers) were allowed to be used during testing. Children who participated in the study showed both Equinus and Crouch gait patterns with disability ranging from very mild to moderately severe. All experimental procedures were performed according to a protocol approved by Spaulding Rehabilitation Hospital Internal Review Board. Data collection was performed in three different conditions as described below.

1) Laboratory Testing

During laboratory testing sessions, data was collected under controlled conditions in the Motion Analysis Lab. ActiveGait system was set in the continuous mode of operation and it gathered data for a set period of time. Data was collected while subjects walked on level ground, up and down a ramp and up and down a stairway. Subjects were asked to perform the tests at a comfortable self-selected speed. In each condition, we collected at least 5 trials with data suitable for estimating the CoP trajectories. The analyses presented in this paper mainly focus on level walking. Subjects were simultaneously videotaped for later analysis by an expert clinician, who provided an assessment of the severity of gait abnormalities based on a clinical scale (Edinburgh Visual Gait [9]). All subjects completed this part of the test.

2) Field Testing

During field testing, subjects were instructed to follow a predetermined path within the hospital environment. The ActiveGait system was set in the continuous mode of operation and it gathered data for a set period of time. All subjects performed level ground walking and ramp ambulation while stair ambulation was performed only when deemed safe by an experienced physical therapist. Subjects walked at self-selected comfortable walking speed and were allowed to rest as needed. The field testing sessions were designed to gather data in a more naturalistic condition compared to the data gathered during laboratory testing. Field testing sessions also provided us a step between lab and home-based data collections. Subjects were videotaped for later analysis of gait abnormalities by an expert clinician. 8 of the recruited children completed this part of the test.

3) Home Testing

One of the recruited children was randomly selected for home monitoring. Data was gathered in the home setting during a period of5 days. The subject was asked to wear the shoe during the performance of daily activities. The ActiveGait system was programmed to collect data in the Normal Mode of operation and started by the researches in the lab before being sent at home with the subject.

C. Feature Extraction

After calculating the CoP trajectories from iSole data, we applied a 5th order Savitzky-Golay filter to smooth the data. From the smoothed CoP trajectories, we then derived a set of 28 features that captured information about the severity of toe-walking. This feature set was based on a retrospective study we previously performed to demonstrate feasibility of the proposed approach [6]. Features were derived for each step and analyzed as separate observations.

D. Classification

Expert clinicians were asked to review the video recordings made during data collection and rate each subject for the severity of gait deviation. Consistently with our previously performed retrospective study [6], we used the Edinburgh Visual Scale (EVS) [9] for rating the severity of

gait deviations. The EVS is an ordinal scale based on 17 observations. Each observation represents a key feature of pathological gait and is rated from -2 to 2, with 0 indicating normal. A deviation in the negative direction indicates a crouch gait pattern whereas one in the positive direction indicates an equinus gait pattern.

As previously done for a dataset collected using a motion analysis camera-based system [6], we trained a Random Forest (RF) [10] classifier with 50 trees based on feature sets derived from the sensorized shoe. The classifier was designed to estimate the scores of the first 7 of the 17 observations of the EVS. RFs are ensembles of weakly correlated decision trees that vote on the classification of a given input. These ensembles have been shown to improve the generalization performance of individual decision trees. In addition, RFs also provide valuable information in the form of internal estimates of generalization error and variable importance. To derive classification accuracy estimates, we trained the classifier on data from the laboratory testing sessions and tested on data from the field and home testing sessions. A leave-one-subject-out analysis was not performed.

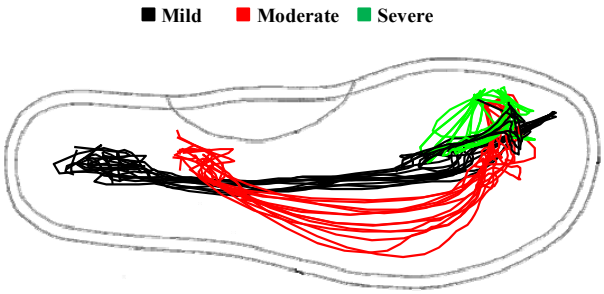

Figure 2. COP trajectories collected by the sensorized insole. Trajectories are shown for different degrees of severity (mild,

III. Results

Figure 2 shows CoP trajectories derived from data collected using the ActiveGait system from three children with different levels of toe-walking severity (mild, moderate and severe). A noticeable difference between the three severity levels can be observed in the characteristics of the corresponding CoP. The CoP of the child with severe toe-walking is mostly located in the forefoot region with very little mediolateral (ML) displacement. The CoP for the kid with moderate toe-walking shows an improvement in the anteroposterior (AP) range while showing an exaggerated ML displacement, indicating that while an abnormality in foot positioning is still present, the child is able to get his midfoot in contact with the ground. The CoP of the child with very mild gait problems shows a near-normal heel-to-toe pattern.

To perform the data analysis, we first performed a 10-fold cross-validation using the Random Forest classifier. Only data collected during the laboratory testing sessions was used for this part of the analysis. We were able to achieve an accuracy level between 96.8% and 100% for the first 7 observations of the EVS. These results showed that it is feasible to estimate measures of toe-walking severity using features extracted from CoP trajectories derived from the ActiveGait system.

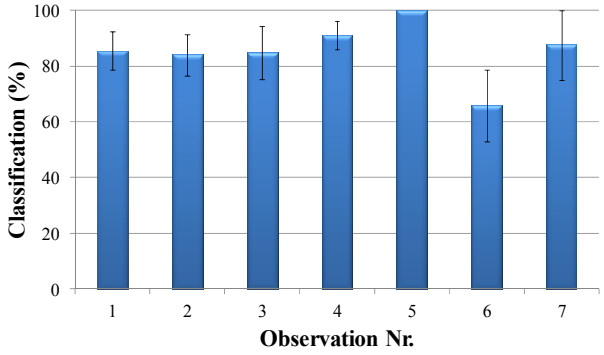

Figure 3. Classification outcome for Observation 1-7 of the Edinburgh Visual Scale. Average and standard error are shown for the 8 subjects from whom we collected data in the field.

Next we trained a Random Forest classifier with 50 trees using data collected from 11 subjects (382 steps) during the the laboratory testing sessions. A classifier was trained for each of the 7 observations of the EVS. The testing set consisted of data collected from a subset of 8 subjects (900 steps) who also completed the field-testing sessions. Figure 3 shows the average classification accuracy with standard error bars for each of the 7 observations. For all the observations, except observation 6, we were able to achieve a classification accuracy of at least 80%. Observation 6 captures the level of disability related to clearance of the foot during the swing phase of a gait cycle. This means that the CoP provides only an indirect measure for this observation and hence, poor accuracy in estimating severity.

The confusion matrix shown in table 1 provides additional information about where the misclassifications occur. We derived the percentage values in the confusion matrix by taking an average across the 7 observations of the EVS. No values are reported for class -2 as that level of severity was not observed for any item of the EVS. The misclassification rate for all classes, except class 0, is around 25%. It is encouraging to see that most of the misclassifications are occurring between adjacent severity levels. This can be explained by the fact that, even though the EVS rates severity from -2 to 2, in reality the severity level is a continuum.

We then tested our classifier on the data collected in the home setting from a single subject over a period of 5 days.

TABLE 1
CONFUSION MATRIX

%		Classified as				
		-2	-1	0	1	2
Actual score	-2					
	-1		73.6	25	1.4	0
	0		2.1	92.3	5.6	0.0
	1		0.5	24.6	74.9	0
	2		0	0	25.7	74.3

During that period, the shoe recorded data for a total of 2 hours. As the data was collected in an unconstrained environment, our first step was to identify data segments belonging to different ambulatory conditions e.g. level walking, stair climbing and standing. After segmenting the data, we identified 198 steps taken by the subject during level walking. First, we trained a Random Forest classifier with 50 trees on data recorded from 11 subjects during only the laboratory testing sessions. A second Random Forest classifier was trained on a training set that included, in addition to the laboratory testing session, a small amount (10 steps) of field data recorded from the subject who underwent the home testing session. In figure 4, we can see a bar plot of the classification accuracy for the home testing session for both conditions. A marked improvement in the classification accuracy was achieved for observation 2 (68% to 94%) and 3 (79% to 98%) when a small amount of field data was included in the training set. This improvement in accuracy can be attributed to the fact that there is a difference between gait patterns observed in a controlled laboratory environment and those observed in the home setting. Classification accuracy greater that 90% was achieved for the rest of the observations under both conditions. These results show the feasibility of using the ActiveGait system for monitoring the severity of gait deviations in children with CP.

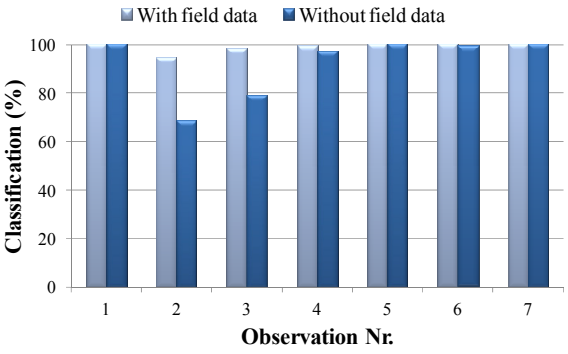

Figure 4. Classification outcome for Observation 1-7 of the Edinburgh Visual Scale. Classification accuracy is shown for data collected in the home environment when we included respectively 0 and 10 steps from the same subject collected in the field in the classifier training set.

IV. Discussion

In this paper, we presented results from the preliminary testing of a novel sensorized shoe called ActiveGait, which has been developed to monitor the severity of gait deviations in children with Cerebral Palsy. We used features extracted from CoP trajectories derived from the shoe data to train a Random Forest classifier for estimating severity scores for the first 7 observations of the Edinburgh Visual Gait scale. The classifier was tested on data gathered during field-testing sessions as well as data gathered from a single subject during home testing.

Classification results showed that it is feasible to estimate severity scores of gait deviations. For the field-testing sessions, we were able to achieve classification accuracy > 80% for 6 out of the 7 observations of the EVS considered in the study. Results were consistent with our earlier retrospective study based on data gathered using a camera-based motion analysis system. A closer inspection of the confusion matrix revealed that most of the misclassifications occurred between adjacent classes. This result points to the fact that the severity of gait deviations spans a continuum. Hence, objective monitoring using an instrumented shoe like the ActiveGait can lead to more fine-grained assessment of progression of the severity of gait abnormalities.

We also presented classification accuracy results for a single subject who used the ActiveGait system in the home setting. We were able to achieve a classification accuracy >90% for all observations when about 10 steps from field testing for that subject were included in the training set. This result points to the fact that subject's gait is altered during observations in controlled environments like a laboratory. Hence, monitoring gait in the home and community settings might give a more accurate picture of their condition.

Preliminary results presented in this paper show that the ActiveGait system can be a useful tool for longitudinal monitoring of toe-walking severity in children with Cerebral Palsy. We are currently working on gathering a larger dataset with subjects wearing the ActiveGait system at home for a period of one week. In the future, we hope to develop a methodology to longitudinally track severity of gait deviations over a period of several months. We believe that long-term monitoring can provide valuable information to clinicians and assist them in making decisions on the appropriate choice and timing of therapeutic interventions.

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