DYNAMIC GAIT STABILITY INDEX BASED ON FOOT-PRESSURE PARAMETERS AND FUZZY LOGIC

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INTRODUCTION

Poor walking stability is a major cause of falls and can lead to a considerable decrease in quality of life [1]. An accurate assessment of mobility problems is therefore critical in the field of physical rehabilitation. Currently, observational evaluations are the only methods used for quickly obtaining balance and stability measures in a clinical setting. These tests generally rate a subject's ability to perform certain actions and movements, and then combine the overall performance as an indication of stability level [2]-[9]. These measures do not produce objective and accurate quantitative results since they often depend on an evaluator's opinion or reaction time. Other techniques of analyzing gait stability use camera and marker-based systems or force plates to obtain accurate and objective data. However, the equipment used in these evaluations is typically confined to a laboratory.

A method of obtaining a fast and accurate gait stability evaluation with a portable system does not currently exist. A solution is to clinically validate a dynamic gait stability index that can be obtained from a single data source, such as plantar foot pressure. Pressure sensitive insoles combined with a portable data-logging system could be used to obtain accurate pressure distribution patterns for different activities in various environments.

This paper describes a method of evaluating gait stability using a single dynamic gait stability index based on six plantar pressure parameters derived from measurements obtained with the F-Scan pressure measurement system, and combined using a fuzzy logic controller. The gait stability index was then validated by testing 15 healthy subjects at four decreasing levels of stability and relating the stability levels with the corresponding stability index values.

METHODS

The F-Scan measurement system uses pressure-sensitive insoles with a grid of 960 force-sensing resistors [10]-[11]. The insole sensor records the normal force in each cell for each frame of data. F-Scan also internally calculates and displays the position of the center of force (COF) for each frame. Six stability parameters were established using preliminary gait data from two subjects in coordination with an extensive literature review in the field of gait evaluation [12].

Anterior-Posterior Parameter

The anterior-posterior (A-P) parameter is a measure the COF motion from front to back of the foot. In a healthy gait stride, the COF should have a smooth transition from the heel to the forefoot [13]. COF motion towards the heel indicates unstable walking. The A-P parameter is a measure of the duration of COF movement toward the heel normalized by stride time.

Medial-Lateral Parameter

The medial-lateral (M-L) parameter measures COF motion in the medial and lateral directions. In a healthy gait stride, the COF should move slightly to the lateral side of the foot during mid-stance and then back to the medial side to terminate the stride [14]. The M-L parameter essentially counts the number of times the COF shifts medially or laterally during a stride.

Maximum Lateral Position Parameter

COF movement to the lateral side of the foot and away from the base of support typically results in a less stable gait pattern [15]. The maximum lateral position parameter is a measure of the most lateral COF position during a stride.

Cell Triggering Frequency Parameter

F-Scan cells should only activate once in an ideal stride. A cell could be continuously activated for any number of consecutive frames, but activating a cell more than once is a sign of abnormal weight shifting, hence an indication of instability. Cell triggering frequency records the maximum number of times a cell is triggered during a stride and is normalized by the total number of frames in the stride.

Stride Timing Parameters

Two temporal parameters are related to gait stability, stride time (ST) and double support time (DST) [16]. ST is the time from the heel-strike of one foot to the following heel-strike of the same foot. DST is the time a person spends with both feet on the ground while walking during a stride..

Fuzzy Logic Controllers

Once the stability parameters were established, they were combined to define an index value. Fuzzy logic controllers are appropriate for this task since they do not require an initial data set to configure the system, and they can be customized according to expected input values and can combine inputs that may not have a clear mathematical association. As well, the controller output can be easily fine-tuned in the future.

The three main aspects of a fuzzy logic controller are the membership functions, rule set, and defuzzification method.

Membership Functions

Each input parameter was mapped to membership functions. By convention, the input value is on the horizontal axis while degree of membership is on the vertical axis. A degree of membership is determined by selecting an input value and projecting vertically to the membership functions. Depending on the membership function layout, each input may project to more than one function. Similarly, membership functions are also created for the output value and are used for defuzzification.

Rule Set

Once each input value has been assigned a degree of membership to the membership functions, the rule set was used to correlate input and output values. Since one input may have a degree of membership to more than one membership function, the fuzzy rule set considered every combination of membership functions between all input variables. For example, For six inputs with four membership functions each, the rule set must account for the 4^6= 4096 possible combinations and assign an output value to each combination.

Defuzzification

After degrees of membership of the input values have been associated with the rule set, the defuzzification process combines the resulting output values to obtain a final output. The Centroid Average (CA) method was chosen for the dynamic stability index fuzzy logic controller because of its reported effectiveness for fuzzy reasoning systems and ease of application to the dynamic stability index system [17]. This method creates a geometric shape based on the output values obtained from the rule set and the output membership functions. The final output is the projection of the centroid of the shape onto the horizontal output value axis.

Clinical Testing

To validate the system, gait data from 15 healthy subjects were analyzed at four decreasing levels of stability. The stability levels were:

1. walking on flat level ground,
2. walking on a 50 mm-thick combination of medium and hard memory foam,
3. walking on the same foam with eyes closed,
4. walking on the same foam with eyes closed after being spun five to fifteen times at approximately 0.5 revolution per second while seated in a chair.

Pressure data was only recorded during mid-gait (once the subject had started walking) to avoid abnormal plantar pressure patterns that may have resulted from gait initiation or termination. The data acquisition trials lasted 7.12 seconds while recording 1000 frames of data at a sampling rate of 140 Hz. Each subject performed five trials for each stability level (a total of 20 trials per subject), at a comfortable self-selected walking pace. A minimum of two people were present during all testing procedures to ensure subject safety.

RESULTS

Table 1 shows the average stability index value across all 15 subjects for each stability level, where the stability index ranges from 0 for highly stable to 1 for low stability. The index values showed an increase across the stability levels and correctly identified the first and last stability levels for 93.3% of the subjects. However, only small differences in stability level were found between the second and third stability levels for 53.3% of the subjects (i.e., “walking on foam” and “walking on foam with eyes closed”). This result is likely due the subjects learning to adapt to the foam or that walking with eyes closed did not actually increase gait instability for normal subjects, especially since data were captured during mid-gait.

Fig. 1 shows the average scaled values of each stability parameter for the four stability levels. This graph demonstrates how the stability parameters tended to increase with instability as well as the small differences between second and third stability levels for most subjects. While A-P, M-L, maximum lateral position, and cell triggering frequency all showed general increases across the four stability levels, as expected, ST and DST both showed small changes with changing condition. This may have been because ST and DST were configured to account for the clinically documented worst-case scenario [16]. The upper limit was likely set too high for the healthy subjects tested in this study (i.e., the values for even the least stable stability level did not approach the ST and DST values for highly unstable stroke patients). These parameters still showed a consistent increase over the stability levels; however, they minimally affected the index since they only varied over a portion of their full range. This can be modified by either adjusting the range of these parameters for subjects without a mobility disability or testing a population with significantly worse gait.

Table 1: Average and standard deviation (in parentheses) of average stability index value for each test condition.

Stability Level	Average Stability Index Value
1	0.227 (0.131)
2	0.273 (0.151)
3	0.262 (0.118)
4	0.401 (0.152)

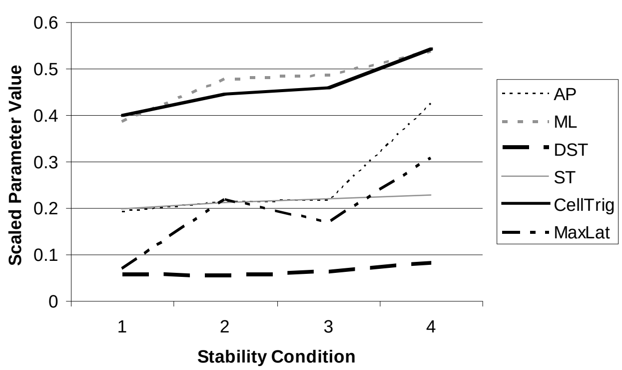

Figure 1: Average values of Anterior-Posterior COF position (AP), Medio-lateral COF position (ML), Double Support Time (DST), Stance Time (ST), Cell Triggering Frequency (CellTrig), Maximum Lateral Force Position (MaxLat), for each test condition.

One crucial step in processing the data, was to divide the raw plantar pressure data from the F-Scan system into strides. There were difficulties associated with an automated stride division algorithm used to separate strides in the raw data. Filtering and threshold algorithms would remove most spike-like noise (due for example, from crumples in the sensor) when the foot was not in contact with the ground. However, in some cases, manual removal of spike-like noise in the raw F-Scan data was required. Improvement in raw pressure data processing, regarding noise removal and thresholding will take place in future work. A more effective stride division algorithm will be developed for future applications of the stability index.

CONCLUSION

In the field of physical rehabilitation, there is currently no portable tool available to quickly and objectively assess a patient's gait stability. This study used the F-Scan plantar pressure measurement system to extract stability parameters that reflect various aspects of dynamic gait stability. A fuzzy logic controller was then used to combine the parameters to obtain a single dynamic gait stability index. Based on the results of the study, the calculated index could correctly rank the four stability levels for 40% of the subjects, and could identify the least and most stable stability levels for 93.3% of the subjects.

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