Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Plantar Pressure Parameters for Dynamic Gait Stability Analysis

Edward D. Lemaire, Ajoy Biswas, and Jonathan Kofman, *Member, IEEE*

Abstract—**Dynamic stability measurement is necessary to evaluate human performance over a variety of locomotor environments. In this paper, the suitability of parameters extracted from plantar-pressure measurements as input into a dynamic stability model was investigated. FScan in-shoe pressure data were collected from 15 subjects as they completed four successively more unstable walking tasks. Six parameters met the criteria of being reliably calculated from plantar pressure data, increasing as the task became more unstable, and relating to past measures from the literature: anterior/posterior centre of force (CoF) position, medio-lateral CoF position, double support time, stance time, cell triggering frequency, and maximum lateral CoF position. These parameters could be combined to create an index of dynamic gait stability.**

I. Introduction

GAIT stability is an important issue for safe locomotion, especially for the elderly and people with disabilities. To properly evaluate dynamic gait stability, stability measurements over a range of tasks and environments are needed (i.e., uneven ground, stairs, ramps, etc.). Typical indoor gait laboratory evaluations are unable to provide this information. An ideal solution would be a quantitative stability index that can be easily applied in a clinical setting and used across physical disabilities. By relating index results to incidence of falls, clinical guidelines can be produced based on the risk of doing various activities. From a research perspective, a reliable and quantitative method to evaluate dynamic gait stability would be used to evaluate medical interventions over a range of applications, from therapies to pharmaceutical interventions to assistive devices. Dynamic, or locomotor, instability shows up in numerous gait parameters, making it difficult to easily interpret and apply dynamic stability assessment in the clinic without data analysis and fusion into a simple and useful tool, such as an index or set of indices.

Stability can be defined as "the property of a body that causes it when disturbed from a condition of equilibrium or steady motion to develop forces or moments that restore the original condition" [1]. Biomechanical measures have been used to evaluate balance and gait stability for over a century [2], [3]. Stable gait is typically characterized by smooth and cyclical kinematic and kinetic curves of the lower-limb segments and body. Increased instability results in larger and more frequent perturbations in dynamic gait data [4]-[13].

Biomechanical gait or postural stability measures are predominately based on force-platform centre of pressure (COP) analysis or interpretation of time-motion or position-velocity curves. While these measures are appropriate for static balance testing, quantitative gait stability comparisons have largely been restricted to level ground walking or standing trials in a motion analysis/gait laboratory. While upper and lower body kinematic data collection is currently unavailable in most clinics, this approach has been used for lab-based locomotor stability studies [11]-[17]. Various data analysis approaches have also been used; including, Floquet-theory alpha values from joint-angle data, whole-body and upper-body momentum from marker-based motion analysis, and perturbations in accelerometer data.

Force plate studies typically examined COP oscillation patterns during standing trials [5], [13], [14]. Krebs et al. [8] determined that a more rapidly dissipating COP oscillation about the position of equilibrium indicated more efficient postural control. Geffen et al. [6] used medio-lateral COP deviations to represent stability during high-heeled gait. Under fatigue conditions, increased lateral COP deviations were thought to represent a lack of medio-lateral foot stability.

Foot pressure analysis has potential as a portable dynamic stability measurement technology. Bauer et al. [4] reported that standing postural sway analysis from plantar COP data was highly repeatable. Dynamic foot-pressure data have been used to predict foot ulceration [25], [26], and have shown differences between biomechanically diverse activities [27] and differences due to gait deficiencies [28]. Discrete pressures values, relative impulse, and stride parameters were used to identify adaptive gait patterns of children with cerebral palsy hemiplegia.

To consider foot pressure analysis as a basis for a stability index, evaluation of potential parameters are required. This paper describes such an evaluation.

II. Methods

A. Pressure Data Collection

A convenience sample of 15 subjects with no physical or biomechanical problems that would affect their walking gait

Manuscript received April 23, 2006.

This research was partly funded by the Natural Sciences and Engineering Research Council of Canada (NSERC).

Edward D. Lemaire is with the Institute for Rehabilitation Research and Development, The Ottawa Hospital Rehabilitation Centre, 505 Smyth Road, Ottawa, ON, Canada, K1H 8M2. (phone: 613-737-7350; fax: 613-737-4260; e-mail: elemaire@ottawahospital.on.ca).

Ajoy Biswas is with the Department of Mechanical Engineering, University of Ottawa (e-mail: ajbiswas@gmail.com).

Jonathan Kofman is with the Department of Systems Design Engineering, University of Waterloo, Waterloo, Canada (e-mail: jkofman@ engmail.uwaterloo.ca).

1-4244-0033-3/06/$20.00 ©2006 IEEE.

were recruited from staff and students at The Ottawa Hospital Rehabilitation Centre and the University of Ottawa. These subjects were fit with F-Scan pressure sensor insoles (Tekscan Inc.) and the insoles were connected to a data collection computer. The F-Scan system was used to collect plantar pressure data at 140 Hz, over five trials, at four test conditions:

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 while seated in a chair.

These conditions provided progressively more unstable situations. Therefore, this data could be used to assess parameter sensitivity for inclusion in a stability index.

B. Parameter Extraction

Following data collection, the F-Scan output was processed using custom-built software. 1000 raw data frames from the left and right foot (2000 frames in total) were filtered before dividing the filtered data into strides and calculating the stability parameters for each stride. Centre-of-force (CoF) values were calculated and exported from the F-Scan software.

A series of parameters that could be extracted from plantar pressure data and were supported by successful applications in the literature were selected for analysis.

1) Frequency Analysis

A Fourier transform was applied to the CoF position data to determine the dominant frequencies. Higher frequencies would indicate higher instability. Unfortunately, fluctuations occurred throughout the data at varying frequencies. Also, dominant frequencies in valid foot pressure data were difficult to accurately extract due to problems distinguishing noise from biomechanical deviations. Therefore, no discernable pattern was identified between instability levels and frequency analysis results.

2) Centre of Force versus Maximum Force

The maximum force (MF) position is defined as the sensor grid row and column with the highest pressure value. CoF position curves from the F-Scan system were much smoother than the MF positions calculated from filtered F-Scan pressure data. F-Scan calculates CoF position to the hundredth of a cell position, thereby leading to a smoother CoF transition between frames. To remove spike-like noise, in the MF signals, a 3 x 3 median filter was applied to the MF data. However, MF position presented the same problems as CoF position in terms of a reliable stability parameter.

3) Anterior/Posterior (A/P) Stability

During stable gait, CoF should move smoothly from the heel to the forefoot. Any backward shifts in COF position are signs of instability. The CoF A/P position-time curve should move in the negative direction, from high row numbers to low row numbers, and therefore should have a negative slope throughout the stride. A positive slope would indicate unsmooth forward progression. The number of zero-crossings of the 1st derivative would be proportional to the number of times the subject's CoF moved backwards. This parameters was sensitive to changes in gait stability

4) Medio-lateral (M/L) Stability

Medio-lateral (M/L) stability analysis is slightly different from the A/P analysis because the CoF M/L curve is expected to move laterally until mid-stance and return to the medial side of the foot during push-off (Fig. 1). To analyze this motion, the 1st derivative of the M/L COF position was used to look for transitions between positive and negative slopes of the M/L- time curve. To isolate important stability information, a dual threshold was implemented. The threshold triggered only when the data crossed both thresholds. The threshold would not trigger if the data fluctuated over one threshold numerous times.

In Fig. 1, a zero-crossing in the velocity-time curve would indicate CoF movement from right to left. The threshold triggered when the COF velocity increased to 0.2. Therefore, the subject would have to shift their CoF substantially in the M/L direction to trigger the threshold. Small variations seen in the CoF velocity curve would be ignored. The M/L stability parameter was calculated as the number of times the alternating threshold was triggered and is an indicator of the number of shifts in body centre of gravity in the medio-lateral direction.

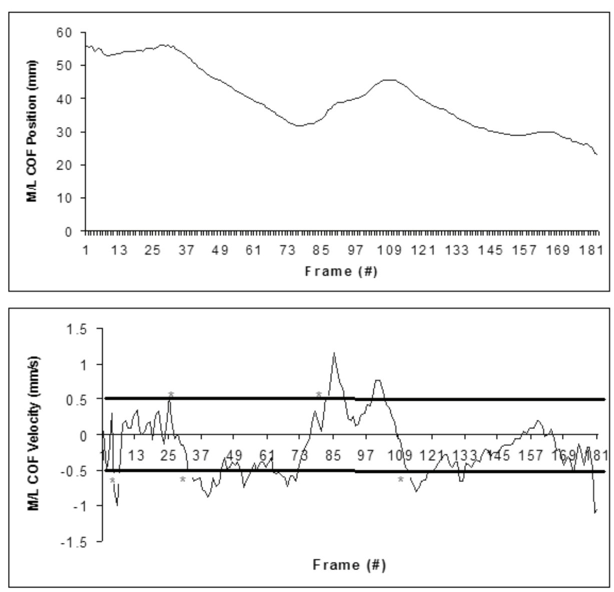

Fig. 1: M/L position and velocity of an unstable stride versus frame number. The dual threshold is set at -0.5 and 0.5 of the M/L COF velocity graph.

5) Maximum Lateral Placement of Force

The F-Scan column data represents the medio-lateral position. Since lateral plantar pressure values relate to lateral movement of the subject's total body centre of gravity away from the base of support, maximum lateral placement of force is an important factor in determining overall gait stability. Extreme COP lateral placement can cause instability and even falls.

To detect extreme COP lateral placement, the MF data was searched to obtain the value and row/column position of the maximum registered pressure in each frame of F-Scan data. To find the maximum lateral placement of force, the frame with the furthest lateral MF column value was isolated and compared to the width of the sensor. The closer the MF value to the lateral side of the foot, the more unstable the subject.

6) Cell Trigger Frequency

As mentioned previously, an ideal stride progresses smoothly from heel to forefoot. As a result, F-Scan cells that come into contact with the foot should only activate once throughout an ideal stride. A cell could be held in the 'ON' position for a number of frames, but once deactivated the cell should not be triggered again. Activating a cell more than once is a sign of abnormal weight shifting, hence an indication of instability. Therefore, the frequency that cells are triggered more than once during a stride can be used as a parameter for a gait stability index. To obtain this parameter, sequential frames of filtered F-Scan data were tagged with an 'ON' or 'OFF' label. The number of times each cell was triggered throughout a stride was monitored and the cell that triggered most often was noted. The cell trigger frequency parameter was also normalized to account for the number of samples in the stride by dividing the cell trigger frequency by the total number of frames (i.e., normalizing to 100% of stance time).

7) Stride Parameters

Stride time (ST) and double support time (DST) have a direct correlation to gait stability. ST is the time from heel-strike to heel-strike of one foot. DST is the time during which both feet are in contact with the ground (i.e.,in double support). Both ST and DST have been found to increase as gait becomes more unstable. These parameters can be extracted after the F-Scan data is divided into strides.

Given this initial evaluation of potential parameters, six parameters were selected for analysis: A/P CoF position, M/L CoF position, Maximum Lateral Position, Cell Triggering Frequency, Stride Time, and Double Support Time.

III. Results

The average values and standard deviations of the raw stability parameters can be seen in Table I. The graph in Fig. 2 demonstrates how most of the variables tended to increase with each test condition. Both ST and DST however, did not vary substantially between stability levels. The A/P, M/L, and Cell Triggering Frequency values showed little change between the second to the third stability levels while Maximum Lateral Position showed a negative change.

TABLE I.
AVERAGE AND STANDARD DEVIATION (IN BRACKETS) OF SIX STABILITY PARAMETERS FOR EACH TEST CONDITION

(A/P=ANTERIOR/POSTERIOR COF POSITION, M/L=MEDIO-LATERAL COF POSITION, DST=DOUBLE SUPPORT TIME (S), ST=STANCE TIME (S), CELLTRIG=CELL TRIGGERING FREQUENCY, MAXLAT=MAXIMUM LATERAL FORCE POSITION).

Condition	1	2	3	4
A/P	0.193 (0.159)	0.214 (0.163)	0.215 (.0161)	0.428 (0.225)
M/L	0.387 (0.277)	0.478 (0.229)	0.184 (0.144)	0.237 (0.160)
DST	0.166 (0.135)	0.163 (0.088)	0.184 (0.144)	0.237 (0.160)
ST	1.101 (0.189)	1.161 (0.190)	1.190 (0.285)	1.233 (0.258)
CellTrig	0.400 (0.177)	0.445 (0.221)	0.458 (0.272)	0.548 (0.244)
MaxLat	0.069 (0.242)	0.220 (0.237)	0.170 (0.236)	0.311 (0.209)

As shown in Fig. 2, the parameter values for test conditions 2 and 3 were not substantially different. Since the subjects did not have balance problems, the experimental setup did not necessarily provide an increase in instability between "walking on foam" and "walking on the same foam with eyes closed". Future studies with a similar protocol could omit the eyes-closed step. It is possible that there was a training effect, where performed trials on the foam alone was training for walking on the foam with eyes closed. A random ordering trails at the various test conditions could be used to remove a possible training effect.

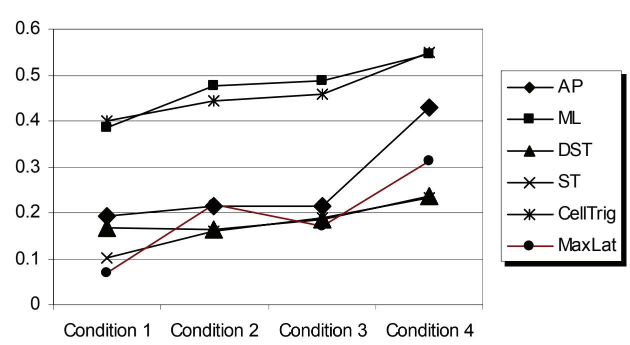

Fig. 2: Average values of Anterior/Posterior CoF position (AP), Medio-lateral CoF position (ML), Double Support Time (DST), Stance Time – scaled (ST), Cell Triggering Frequency (CellTrig), Maximum Lateral Force Position (MaxLat), for each test condition.

Following evaluation of the data extraction process, improvement automation is required for determining accurate stride parameters (onset and completion of stance-phase) from F-Scan plantar pressure data. Since most measures are based on accurate data-set division into strides, an error in stride segmentation leads to many potential errors. Since mean filers, median filters, and threshold algorithms may not remove erroneous pressure readings, automated stride sectioning often lead to a longer stance-phase period. These erroneous pressure values were also identified as maximal forces for some trials. Therefore, all trials were manually screened and adjusted for this research. This was a viable solution given the small population tested; however, a more effective automatic stride division algorithm is needed for broad application.

IV. Conclusion

Currently, a viable approach for measuring gait stability in real-world environments is lacking. New mobile plantar pressure measurement systems can collect data for development of a dynamic gait stability index. Based on the results of this study, A/P CoF position, M/L CoF position, double support time, stance time**,** cell triggering frequency, and maximum lateral force position are viable parameters for inclusion in such an index. These parameters were sensitive to changes in walking stability and can be reliably extracted from in-shoe plantar-pressure system output.

Acknowledgment

The authors acknowledge the technical support of Shawn Millar and facility/clinical support from The Ottawa Hospital Rehabilitation Centre GAMA laboratory and the Total Foot Care service.

References

[1] Merrian-Webster Online Dictionary. http://www.m-w.com/cgi-bin/dictionary?book=Dictionary&va=stability&x=14&y=20. Checked December 8, 2004.

[2] F.B. Horak, S. M. Henry, A. Shum-Cook, "Postural perturbations: new insights for treatment of balance disorders," *Physical Therapy*, vol. 77, no. 5, pp. 517-533, 1977.

[3] K. Berg, K. E. Norman, "Functional assessment of balance and gait," *Clin Geriatr Med*, vol. 12, no. 4, pp. 705-723, 1996.

[4] J. A. Bauer, J. H. Cauraugh, M. D. Tillman, "An insole pressure measurement system: repeatability of postural data", *Foot Ankle Int*, vol. 21, no. 3, no. 221-226, 2000.

[5] E. C. Jansen, "Postural stability by foot-to-ground force measurement," *Dan Med Bull*, vol. 35, no. 5, pp. 479-493, 1988.

[6] A. Gefen, M. Megido-Ravid, Y. Itzchak, M. Arcan, "Analysis of muscular fatigue and foot stability during high-heeled gait," *Gait Posture*, vol. 15, pp. 56-63, 2002.

[7] D. E. Krebs, A. M. Jette, S. F. Assmann, „Moderate exercise improves gait stability in disabled elders," *Arch Phys Med Rehabil*, vol. 79, no. 12, pp. 1489-1495, 1998.

[8] D. E. Krebs, C. A. McGibbon, D. Goldvasser, "Analysis of postural perturbation responses," *IEEE Trans Neural Syst Rehabil Eng*, vol. 9, no. 1, pp. 76-78, 2001.

[9] D. Moxley Scarborough, D. E. Krebsa, B. A. Harris, "Quadriceps muscle strength and dynamic stability in elderly persons," *Gait Posture*, vol. 10, no. 1, pp. 10-20, 1999.

[10] S. Valerie, G. Cobb, "Measurement of postural stability before and after immersion in a virtual environment". *Appl Ergon*,vol. 30, no. 1, pp. 47-57, 1999.

[11] Y. Hurmuzlu, C. Basdogan, D. Stoianovici, "Kinematics and dynamic stability of the locomotion of post-polio patients" *J Biomech Eng*, vol. 118, no. 3, pp. 405-411, 1996.

[12] A. Scheiner, D. Ferencz, H. Chizeck, "Quantitative measurement of stability in human gait through computer simulation and floquet analysis," *IEEE-EMBC and CMBEC Theme 6: Physiological Systems/Modelling and Identification*, pp. 1489-1490, 1997.

[13] P. B. Tharpa, P. Gideon, R. L. Fought, M. Kormicki, W. A. Roy, "Comparison of clinical and biomechanical measures of balance and mobility in elderly nursing home residents," *J Am Geriatr Soc*, vol. 42, pp. 493-500, 1994.

[14] B. K. Kaya, D. E. Krebs, P. O. Riley, „Dynamic stability in elders: momentum control in locomotor ADL," *J Gerontol Series*, vol. 53, no. 2, pp. 126-134, 1998.

[15] J. L. Patton, Y. Pai, W. A. Lee, "Evaluation of a model that determines the stability limits of dynamic balance," *Gait Posture*, vol. 9, no. 1, pp. 38-49, 1999.

[16] H. J. Yack,R. C. Berger, „Dynamic stability in the elderly: identifying a possible measure," *J Gerontol*, vol. 48, no. 5, pp. 255-230, 1993.

[17] J. B. Dingwell, J. P. Cusumano, P. R. Cavanagh, D. Sternad, "Local dynamic stability versus kinematic variability of continuous overground and treadmill walking," *J Biomech Eng*, vol. 123, pp. 27-32, 2001.

[18] *Ranchos Los Amigos Medical Center. Observational gait analysis handbook*. CA: Los Amigos Research and Educational Institute, 1989.

[19] K. Berg, S. Wood-Dauphinee, J. I. Williams, B. Maki, "Measuring balance in the elderly: Validation of an instrument," *Can J Public Health*, vol. Suppl 2:S7, pp. 11, 1992.

[20] L. Seaby, G. Torrance, "Reliability of a physiotherapy functional assessment used in a rehabilitation setting," Physiother Can, vol. 41, pp. 264-271, 1994.

[21] D. Podsiadlo, S. Richardson, "The timed "Up & Go": a test of basic functional mobility for frail elderly persons," *J Am Geriatr Soc*, vol. 39, no. 2, pp. 142-148, 1991.

[22] M. W. Legro, G. D. Reiber, D. G. Smith, M. del Aguila, J. Larsen, D. Boone, "Prosthesis evaluation questionnaire for persons with lower limb amputations: assessing prosthesis-related quality of life," Archives of Physical Medicine and Rehabilitation. 1998;79(8):931-938.

[23] Miller WC, Speechley M, Deathe B. The prevalence and risk factors of falling and fear of falling among lower extremity amputees. *Arch Phys Med Rehabil*, vol. 82, pp. 1031-1037, 2001.

[24] A. Forster, J. Young, "Incidence and consequences of falls due to stroke: a systematic inquiry," *BMJ*, vol. 311, pp. 83-86, 1995.

[25] P. R. Cavanagh, J. S. Ulbrecht, "Clinical plantar pressure measurement in diabetes: rationale and methodology," *Foot*, vol. 4, pp. 123-135, 1994.

[26] L. Avery, D. G. Armstrong, R. P. Wunderlich, J. Tredwell, A. J. M. Boulton, "Predictive value of foot pressure assessment as part of a population-based diabetes disease management program," *Diabetes Care*, vol. 26, no. 4, no. 1069-1073, 2003.

[27] K. S. Maluf, R. E. Morley,E. J. Richter, J. W. Klaesner, M. J. Mueller, ‚Foot pressures during walking are strongly associated with pressures during other ambulatory activities in subjects with diabetic neuropathy," *Arch Phys Med Rehabil*, vol. 85, no. 2, pp. 253-260, 2004.

[28] V. Femery, P. Moretto, H. Renaut, A. Thévenon, G. Lensel, "Measurement of plantar pressure distribution in hemiplegic children: changes to adaptive gait patterns in accordance with deficiency," *Clin Biomech*, vol. 17, no. 5, pp.406-413, 2002.