35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Potential to Fall of Bipeds Using Foot Kinematics

Andrew Peter Vogt, Dr. Andrew Merryweather, Dr. Kurt Beschorner,
and Prof. Stacy J. M. Bamberg *IEEE Senior Member*

***Abstract*— This research compares normal to unexpected slipping gaits of healthy adults to detect potential to fall. Using various x, y, and z position analyses, including a Root Mean Squared Error (RMSE), significant differences are shown between normal and unexpected slipping gaits. Our results show that after heel strike of the slipping foot, the recovery foot rapidly changes position to restore balance and lower falling potential. We found RMSE of the recovery foot is significantly greater than the slipping foot, and that potential to fall is easily quantifiable through comparing normal to unexpected gaits. This research provides a solid foundations for a generalized understanding of fall potential for various gaits.**

I. INTRODUCTION

Liberty Mutual Research Institute for Safety had indicated nearly a 37% increase in same level falls experienced by people over the past 10 years. Falls on same level represent the second most costly form of disabling injury, representing $7.7 billion dollars per year [1], and are certainly an important issue for many researchers [2], [3], [4], [5], [6], [7] (to name a few).

A variety of attempts have been used to prevent falling. Our focus is to decrease the risk of fall through training. Studies show older adults are capable of reducing chances of falling by a factor of 7 if subjected to repeated slip events [8].

Movement Analysis (MA) is an excellent tool for improving physical skills by providing clear visual indicators of pathologic, in our case slipping, gait through comparison to a normal gait. These differences help define Potential to Fall (PF) and can be quantified using a Root Mean Squared Error (RMSE). Describing 'stability' of human motion is incredibly difficult and subjective; many could argue that even a walking gait is unstable motion. PF is developed in this paper as an alternative to stability applies to human motion. FP is shown to be high if a person has a higher probability of falling and low if otherwise.

This research continues an investigation of bipedal slip from two publications: [9] implemented a low cost wearable sensor capable of identifying slip in real time. [10] used a motion/force capture laboratory to evaluate force contact and slip relationships. Both publications only tested one or two subjects under predictable slipping conditions. Needing to direct the focus toward gait training, this paper looks at comparing kinematic data of multiple subjects experiencing an unexpected slip. The following sections outline out methods, results, a discussion of those results, future work, and conclusions.

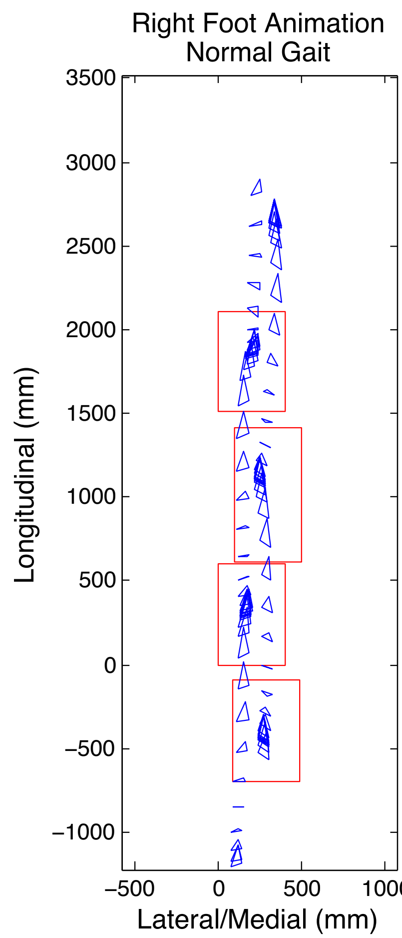

Fig. 1. Birdseye view of a typical normal gait. The four rectangles represent boundaries of the force plates. Valid subjects was selected if only one foot made contact with a unique force plate.

II. METHODS

Fig. 1 illustrates the testing environment. Four six-Degree of Freedom (DOF) Force Plates (FPs), illustrated with the red-outlined rectangles, were used with a right-left-right-left foot stepping pattern so that one foot would uniquely contact

A. P. Vogt is Faculty of Engineering at Salt Lake Community College, Salt Lake City, UT, U.S.A. andrew.peter.vogt@gmail.com
A. Merryweather is Faculty of Mechanical Engineering, University of Utah, Salt Lake City, UT, U.S.A. a.merryweather@utah.edu
K. Beschorner is Faculty of Materials Engineering, University of Wisconsin - Milwaukee, Wilwaukee, WI, U.S.A. beschorn@uwm.edu
S. J. M. Bamberg is Faculty of Mechanical Engineering, University of Utah, Salt Lake City, UT, U.S.A. phone: 801.585.9081 sjm.bamberg@utah.edu

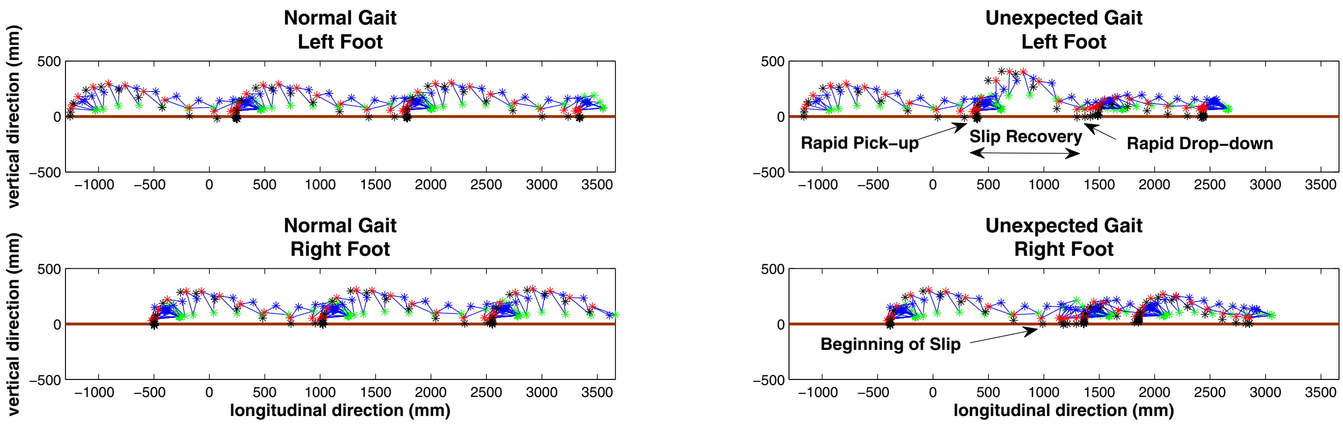

Fig. 2. Comparison of normal and unexpected slip walking gaits for both feet of Subject A, Trial 3. Red, blue, and green asterisk represent the heel, ankle, and toe markers, respectively. The black asterisk is a calculated heel marker which makes ground contact, and the brown line represents the ground.

one FP. With the exception of FP3, all FPs were always kept dry.

To ensure normal gait, and good baseline data, subjects were assured dry surface conditions during the first few trials. After the baseline trials, and without the subject's knowledge, a diluted glycerol solution, of 75% Glycerol and 25% Water, was applied to FP3. FPs 1, 2, and 4 were 400mm wide and 600mm long (see Fig. 1), and FP 3 was 400mm wide but 800mm long. FP3s extra length helped ensure force data was captured for both the normal and slipping event. It is difficult for subjects to see the difference in the size of FPs because the flooring surface on both FPs and the surrounding floor are the same size and color. Subjects are not told what the FPs are or their function, so they do not have a good reason to modify their gait to strike the FPs cleanly.

The data was collected as part of a larger project analyzing effects of aging and posture on slipping. Written informed consent was approved by the University of Wisconsin Internal Review Board. Subjects were fitted with 79 motion capture markers, a safety harness, and the same type of footwear.

Fig. 2 shows a sample comparison between normal and slip gaits for a single subject. The bold-brown solid line at zero represents ground, and the red, blue, and green markers represent the heel, ankle, and toe, respectively. For walking, the heel often strikes ground first. However, the heel markers do not coincide with the true heel contract point. A contact point, shown by the black marker on Fig. 2, is calculated using a known standing vertical distance each subject's heel marker and the ground. The left and right subfigures illustrate normal and unexpected slip gaits, respectively. The upper and lower subfigures show the left and right foot, respectively.

III. ANALYSIS

Four subjects (A, B, C, and D), who experienced severe slips, were selected for analysis. Subject A had four recored normal gaits and Subjects B, C, and D had five recored normal gaits. Every subject had one unexpected slipping gait, where they were unaware of what trial the unexpected slip would occur. The results compared normal and unexpected three-dimensional kinematics, as shown in previous figures, and an RMSE calculation.

The RMSE compares each subjects's $n = 4$ or $n = 5$ normal gaits to each other, and to the unexpected slipping gait. Consider the following data sets:

$$K_{A,B,C,D} = \begin{bmatrix} k_{1,1} & \dots & k_{1,n} \\ \vdots & \vdots & \vdots \\ k_{300,1} & \dots & k_{300,n} \end{bmatrix} \tag{1}$$

$$U_{A,B,C,D} = \begin{bmatrix} u_1 \\ \vdots \\ k_{300} \end{bmatrix} \tag{2}$$

where K is an array of known data consisting of n normal gaits (number of rows) and 300 data points (number of columns) each. The set of unknown data, represented by U also has 300 data points, but only one trial dataset. There are 4 sets of unknown and known data sets corresponding to each of the 4 young and healthy subjects (A,B,C, and D). All data points in K and U are shifted to begin at a common x, y, and z coordinate. Data shifting ensure mores accurate averaging of the normal data, a clearer comparison between normal and unexpected data, and higher confidence that contact on FP3 happens at approximately the same time for all normal and unexpected trials. To ensure a clear correlation between the sets of normal data, an average is calculated,

$$K_{avg} = \begin{bmatrix} \frac{\sum_{i=1}^{n} k_{1,i}}{n} \\ \vdots \\ \frac{\sum_{i=1}^{n} k_{300,i}}{n} \end{bmatrix}. \tag{3}$$

Further insight comes from splitting the data at the point of heel contact for the unexpected trial of FP 3, resulting in

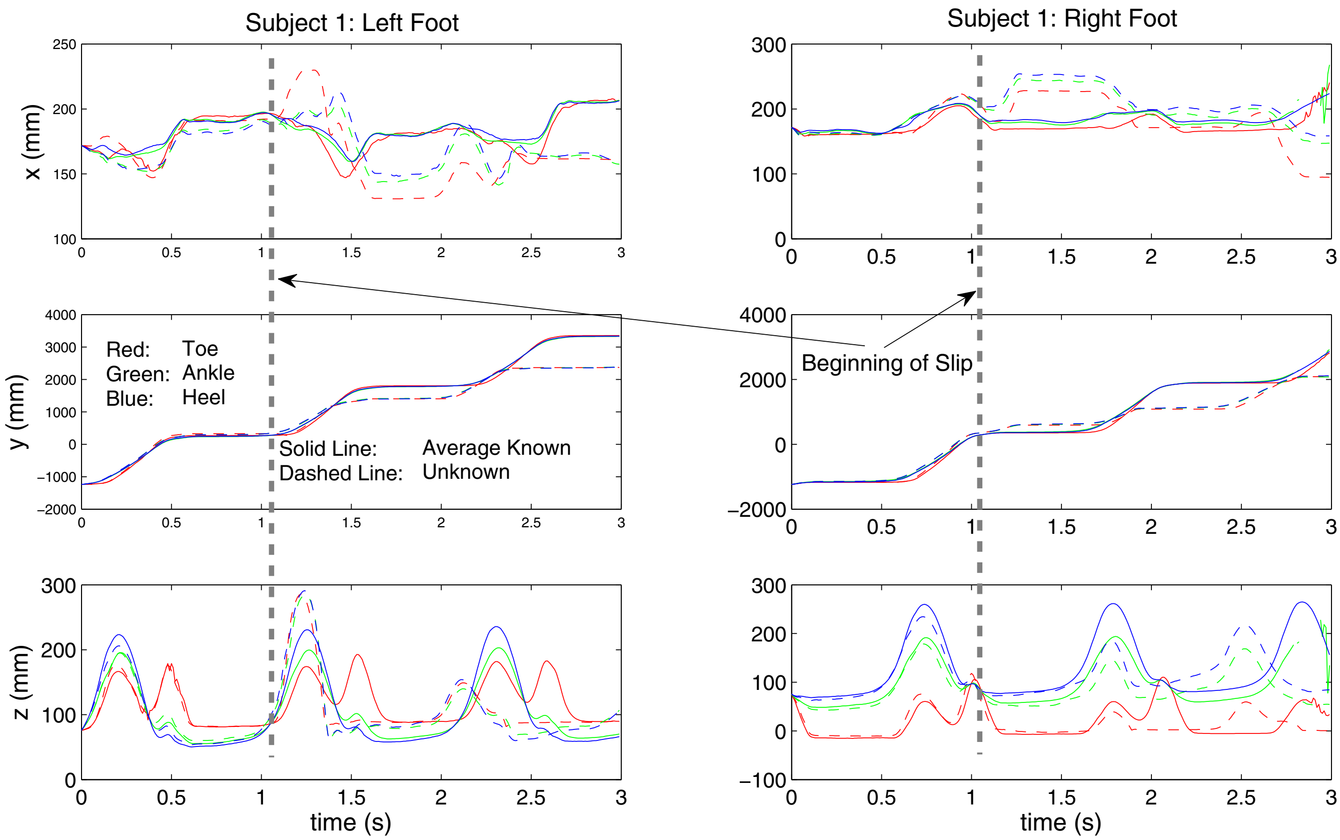

Fig. 3. Subject 1 x, y, and z markers for the toe, ankle, and heel. The solid line indicates the average normal trials and the dashed line indicates the unexpected trial. The vertical dashed line indicates the where unexpected slip occurs and the approximate time when the right foot strikes FP3.

split versions of (3)

$$K_{avg_{1\rightarrow FP3-1}} = \begin{bmatrix} kavg_1 \\ \vdots \\ kavg_{FP3-1} \end{bmatrix} \tag{4}$$

$$K_{avg_{FP3\rightarrow 300}} = \begin{bmatrix} kavg_{FP3} \\ \vdots \\ kavg_{300} \end{bmatrix} \tag{5}$$

In addition to visual inspection, RMSE is calculated to quantify the correlation between normal trials,

$$K_{RMSE_{1\rightarrow FP3-1}} = \frac{\sum_{i=1}^{FP3-1}}{FP3-1} \begin{bmatrix} \sqrt{(k_{avg_i} - k_{i,1})^2} \\ \vdots \\ \sqrt{(k_{avg_i} - k_{i,n})^2} \end{bmatrix}^T \tag{6}$$

$$K_{RMSE_{FP3\rightarrow 300}} = \frac{\sum_{i=FP3}^{300}}{300-(FP3-1)} \begin{bmatrix} \sqrt{(k_{avg_i} - k_{i,1})^2} \\ \vdots \\ \sqrt{(k_{avg_i} - k_{i,n})^2} \end{bmatrix}^T, \tag{7}$$

where (6,7) build row vectors compute the RMS value for each of the n trials. Then, the total RMSE for all n trials is computed using

$$\kappa_{RMSE_{1\rightarrow FP3-1}} = \frac{\sum_{j=1}^{n} K_{RMSE_{1\rightarrow FP3-1}}}{n} \tag{8}$$

$$\kappa_{RMSE_{FP3\rightarrow 300}} = \frac{\sum_{j=1}^{n} K_{RMSE_{FP3\rightarrow 300}}}{n} \tag{9}$$

where κ is the scalar sum of vector components of K_{RMSE}. One would expect $K_{RMSE_{1\rightarrow FP3-1}} < K_{RMSE_{FP3\rightarrow 300}}$ because gait naturally deviates over time.

While comparing similarities between known trials, RMSE also helps compare the differences between the average of the known trials to the unexpected trials. Similar to how (6) and (4) were split, the unexpected data is also split at the same point as follows

$$U_{1\rightarrow FP3-1} = \begin{bmatrix} u_1 \\ \vdots \\ u_{FP3-1} \end{bmatrix} \tag{10}$$

$$U_{FP3\rightarrow 300} = \begin{bmatrix} u_{FP3} \\ \vdots \\ u_{300} \end{bmatrix} \tag{11}$$

We also calculate the RMSE of both (10) and (11) datasets,

$$U_{RMSE_{1\to FP3-1}} = \frac{\sum_{i=1}^{FP3-1}}{FP3-1} |k_{avg_i} - u_i| \quad (12)$$

$$U_{RMSE_{FP3\to 300}} = \frac{\sum_{i=FP3}^{300}}{300-(FP3-1)} |k_{avg_i} - u_i|, \quad (13)$$

where (12,13) can be compared to (8,9) to correlate unknown and known datasets. A low numerical difference between (12) and (8) would indicate validity because the curves would be nearly coincident before slip. If a high numerical difference between (13) and (9) exists, then a significant PF would be expected.

IV. Results and Discussion

The kinematic results is shown in Fig. 2 and 3; the RMSE results are shown in Table I and Fig. 4.

A. Kinematics

When comparing normal to slip gaits, Fig. 2 illustrates a significant deviation between both the slipping (right) and recovery (left) feet. Normal gaits show a smooth transition as one foot strikes and the other gradually picks up to maintain balance. When a foot strikes a slippery surface, on the other hand, the other foot makes an abrupt motion to recover balance. Fig. 2 shows the left (recovery) foot lifts up and lets down in nearly half the longitudinal distance of a normal gait.

These rapid changes are also reflected in Fig. 3 which compare average normal (solid line) to unexpected slip (dashed line) for the toe (red), ankle (green), and heel (blue).The beginning of slip (thick gray dashed vertical) line, placed just after 1s, shows the approximate location of where the right foot strikes the FP3. Notice the rapid separation between the known (solid) and unknown (dashed) kinematics after unexpected slip. After this point, the normal gait is reasonably periodic, the unknown gait is quite stochastic. While slipping, the right foot instantaneously picks up speed in the medial and longitudinal directions with very little change in the vertical direction. After about 2s have passed, the unexpected gait begins to resume periodic behavior of a normal gait. The drastic difference between periodic illustrates that kinematics are an excellent metric for PF.

The left foot's recovery effort is shown by rapid vertical (z), and medial (x) motion. The vertical motion is no real surprise, and is already shown in Fig. 2, but the medial motion is quite interesting because it shows the effort to almost instantaneously widen the base of support to help prevent fall. The rapid medial motion of the toe, in relation to the other markers, further indicates this need to widen the base of support. These rapid movements indicates increased potential to fall. More subtle movements, are reflected as less potential to fall.

B. RMSE

RMSE data is presented Table I which combines all subject and foot marker data together with corresponding averages and standard deviations. Because of a potentially slippery FP3, the data is split between steps 1-2 and 3-4.

Fig. 4 presents the information in Table I graphically to better visualize PF of normal gaits, with respect to each other, and with respect to unexpected gaits.

Considering Table I, notice the rows of average known versus unexpected RMSE trials for steps 1-2. The RMSE average and standard deviation values are small and similar. When plotted, as the first subfigure in Fig. 4, the linear zero-intercept trend-lines have a nearly one-to-one slope. The indicates the first two steps of the unexpected trail can be classified as normal steps; if the subject anticipated a slip, it is likely this data would not be as well correlated. The one-to-one correlation helps conclude a low PF.

The one-to-one correlation supporting low PF is further supported when comparing rows of known versus unexpected RMSE for steps 3-4 on Table I and the second subfigure of Fig. 4. Between these steps, the known RMSE average and standard deviation values stay relatively low compared to the unexpected data; instead of a one-to-one correlation (for both mean and standard deviation), this now results in a 2.4-to-1 and 3.6-to-1 correlation for average and standard deviation, respectively. Both higher correlations indicated an elevated PF.

The previous comparison becomes stronger by comparing known RMSE trials of steps 1-2 and 3-4 presented by the third subfigure of Fig. 4. The slightly larger than one-to-one correlation is acceptable because gait naturally deviates over time; it is still far less than the unexpected gait presented in the second subfigure. PF is still low especially considering the longer time-lapse of the gait.

V. Future Work

PF analysis will be extended using more data from the subjects presented in this paper. We will look upper body markers to illustrate the center of mass movement in relation to the feet, and center of pressure, shear, and normal forces at the surface contact. All sources of data will be fused for an even clearer understanding of PF.

PF will help better understand bipedal movement in various gaits. Another upcoming project will instrument ski boots of skiers with Force Sensitive Resistors (FSRs) and Inertial Measurement Units (IMUs) to better understand their PF. The study in this paper is a critical foundation for understanding PF in skiers. Skiing instrumentation will be a great educational tool to help ski instructors better understand and control how students can reduce PF.

VI. Conclusion

Potential to fall (PF) is an important new metric because of the difficulty describing stability bipedal gaits. This paper showed various ways which kinematic foot maker data can

	Ankle						Toe						Heel						
Subject Average	**Left (recovery)**			**Right (Slip)**			**Left (recovery)**			**Right (Slip)**			**Left (recovery)**			**Right (Slip)**			
coordinates	x	y	z	x	y	z	x	y	z	x	y	z	x	y	z	x	y	z	
Avg. Known Trials	**1.86**	**2.80**	**0.54**	**1.02**	**2.75**	**0.80**	**3.23**	**3.38**	**0.87**	**3.23**	**3.38**	**0.87**	**2.04**	**3.05**	**0.86**	**1.04**	**3.05**	**1.21**	**Steps 1-2**
stdev +/-	**0.87**	**1.17**	**0.12**	**0.60**	**1.86**	**0.46**	**1.94**	**0.81**	**0.06**	**1.94**	**0.81**	**0.06**	**1.11**	**0.88**	**0.25**	**0.59**	**1.89**	**0.68**	
Unknown Trials	**2.24**	**2.45**	**0.61**	**0.86**	**2.53**	**0.60**	**3.14**	**3.15**	**0.70**	**0.87**	**2.78**	**0.65**	**2.92**	**4.15**	**1.80**	**0.89**	**2.75**	**0.74**	
stdev +/-	**1.01**	**1.92**	**0.34**	**0.46**	**1.76**	**0.29**	**1.92**	**1.98**	**0.28**	**0.36**	**1.79**	**0.34**	**1.84**	**2.98**	**1.68**	**0.34**	**2.38**	**0.50**	
Avg. Known Trials	**2.85**	**5.70**	**0.90**	**2.85**	**4.88**	**1.56**	**3.70**	**6.03**	**1.06**	**3.95**	**6.03**	**1.06**	**2.90**	**5.63**	**1.41**	**2.80**	**5.05**	**1.41**	**Steps 2-4**
stdev +/-	**1.02**	**3.21**	**0.48**	**1.31**	**2.75**	**1.35**	**1.02**	**2.95**	**0.31**	**0.87**	**2.95**	**0.31**	**1.02**	**3.00**	**0.80**	**1.26**	**2.56**	**0.93**	
Unknown Trials	**4.83**	**13.55**	**2.43**	**3.80**	**14.38**	**2.80**	**7.38**	**15.25**	**2.68**	**3.19**	**16.33**	**1.78**	**4.93**	**15.53**	**4.08**	**3.25**	**14.90**	**3.93**	
stdev +/-	3.24	14.76	0.79	0.60	1.86	0.46	4.39	15.12	0.93	1.94	11.93	0.53	3.30	14.22	1.34	0.73	11.49	1.54	

TABLE I

AVERAGE AND STANDARD DEVIATION FOR ANKLE, HEEL, AND TOE MARKER OF THE LEFT AND RIGHT FOOT VERSUS THE KNOWN AND UNKNOWN TRIALS OF THE FIRST AND LAST TWO STEPS. THIS AVERAGES AND STANDARD DEVIATIONS ON THE TABLE HELP INDICATE SIMILARITIES BETWEEN NORMAL GAITS AND DIFFERENCES BETWEEN THE NORMAL AND UNEXPECTED GAITS. UNITS ARE MM.

identify slip and PF. These kinematic foundations can effectively be applied to any biped with simple instrumentation, such as an IMU.

REFERENCES

[1] "Top 10 causes of disabling injuries 2007," tech. rep., 2010 Liberty Mutual Insurance Company, 2010.

[2] S. Gates, J. Fisher, M. Cooke, Y. Carter, and S. Lamb, "Multifactorial assessment and targeted intervention for preventing falls and injuries among older people in community and emergency care settings: systematic review and meta-analysis," *Bmj*, vol. 336, no. 7636, pp. 130–133, 2008.

[3] L. Gillespie, M. Robertson, W. Gillespie, S. Lamb, S. Gates, R. Cumming, and B. Rowe, "Interventions for preventing falls in older people living in the community," *Cochrane Database Syst Rev*, vol. 2, no. 2, 2009.

[4] T. Nikolaus and M. Bach, "Preventing falls in community-dwelling frail older people using a home intervention team (hit): results from the randomized falls-hit trial," *Journal of the American Geriatrics Society*, vol. 51, no. 3, pp. 300–305, 2003.

[5] M. Robertson, A. Campbell, M. Gardner, and N. Devlin, "Preventing injuries in older people by preventing falls: A meta-analysis of individual-level data," *Journal of the American geriatrics society*, vol. 50, no. 5, pp. 905–911, 2002.

[6] M. Tinetti, "Preventing falls in elderly persons," *New England journal of medicine*, vol. 348, no. 1, pp. 42–49, 2003.

[7] J. Zhang, K. Ishikawa-Takata, H. Yamazaki, T. Morita, and T. Ohta, "The effects of tai chi chuan on physiological function and fear of falling in the less robust elderly: an intervention study for preventing falls," *Archives of gerontology and geriatrics*, vol. 42, no. 2, pp. 107–116, 2006.

[8] Y. Pai, T. Bhatt, E. Wang, D. Espy, and M. Pavol, "Inoculation against falls: rapid adaptation by young and older adults to slips during daily activities," *Archives of physical medicine and rehabilitation*, vol. 91, no. 3, pp. 452–459, 2010.

[9] L. S. Lincoln and S. J. M. Bamberg, "Insole sensor system for real-time detection of biped slip," (Buenos Aires, Argentina), pp. 1449 – 1452, 2010. Biomimetic robotics;Bipedal gait;Bipedal locomotion;Detection rates;Human gait;Low costs;Numerous models;Real time;Real-time detection;Robot designers;Sensor systems;Traction control systems;Wearable sensor systems;.

[10] A. Vogt, L. Lincoln, S. J. M. Bamberg, and M. Minor, "Traction force characterization of human bipedal motion," in *IEEE/RSJ Intelligent RObots and Systems (IROS) Conference 2010, Taipei, Taiwan*, 2010.

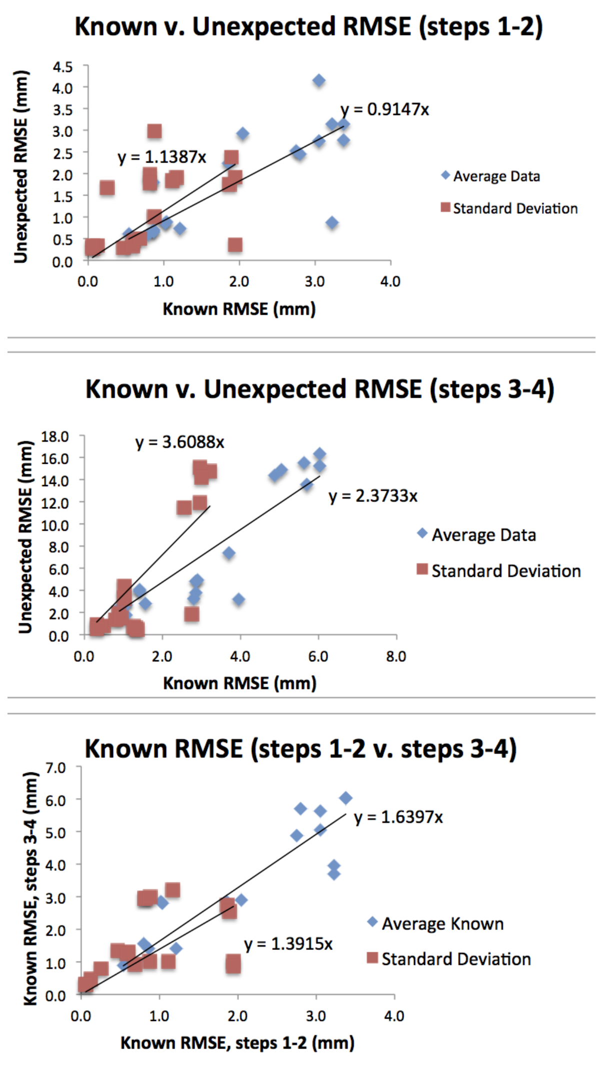

Fig. 4. Plots of RMSE and standard deviation with fitted trend lines having a y-intercept of zero. The trend-line help to correlate the potential of falling. The closer either the average or standard deviation trend-lines are to a slope of one (or one-to-one ratio) indicates a lot PF.