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Computation Method for Available Response Time due to Tripping at Minimum Foot Clearance

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Abstract—**Falls prevention is important for older individuals to maintain healthy lifestyles and is an essential challenge in sustaining the socioeconomic structure of many advanced nations. Tripping has been recognized as the largest cause of falls and accordingly, understanding tripping-induced anterior balance loss is necessary in reducing the overall frequency of falls among older adults. Hazardous anterior balance loss due to tripping can be attributed to the mid-swing phase event, minimum foot clearance (MFC). The mechanism of tripping-induced anterior balance loss can be described as anterior movement of the center of mass (CoM) passing the frontal boundary of the supporting base between the swing and stance toes. The first aim of the current study was to establish a computational method for determining available response time (ART) to anterior balance loss due to tripping at MFC, in other words, the time taken for CoM to reach the anterior boundary and therefore, the time limit for balance recovery. Kinematic information of CoM and both toes in addition to simulated impact force due to tripping at MFC were used to estimate ART. The second aim was to apply correlation analysis to a range of gait parameters to identify the factors influencing ART. ART for balance loss in the forward direction due to tripping was on average. 0.11s for both the dominant and non-dominant limbs' simulated tripping at MFC. Correlation analysis revealed five factors at MFC that prolong ART including: 1) greater fore-aft distance from CoM to stance toe, 2) greater sideway distance from CoM to swing toe, 3) longer distance from CoM to the frontal boundary of the supporting base, 4) slower CoM forward velocity and 5) slower horizontal toe velocity. The established ART computation method can be utilized to examine the effects of ageing and various gait tasks on the likelihood of tripping-induced anterior balance loss and associated falls.**

I. Introduction

Falls among older adults have been recognized as a serious social healthcare issue that urgently requires prevention strategies due to negative impacts on mobility and morbidity, and the considerable medical costs that remain a concern in sustaining health care costs in many developed countries. More than 33% of older adults (> 65 yrs.) fall at least once a year and 10-20% of those result in serious injuries that require long-term hospitalization and often cause permanent loss of body functions [1-5]. Effective and practical falls prevention strategies are therefore expected to be accommodated into everyday lives of older adults for the ever-growing senior population. In the case of the most demographically aged country, Japan, for example, every one percent reduction in falls rate can prevent more than 300,000 older adults from falling and save direct medical costs of approximately $220 million [6-8].

Up to 53% of falls are subsequent to tripping, the leading cause [9-11], defined as an event in which the most distal feature of the swing limb, usually the lowest part of the shoe or foot, makes unanticipated contact with either the supporting surface or objects on it with sufficient force to destabilize the walker [12]. Minimum foot clearance (MFC) is known as the mid-swing phase event where the risk of tripping-associated forward (anterior) falls has been considered most frequent due to the low vertical height of swing toe from the walking surface (i.e. 1.0-2.0 cm) and highest swing toe horizontal velocity, approximately three times walking speed [13-15].

Swing foot at MFC is, in addition, parallel to the stance foot, creating a smaller anterior margin to the frontal boundary of the supporting base (Fig. 1, bottom) [14]. Balance in the transverse plane can be described using the center of mass (CoM) and the virtual base of support [16-18] with balance loss due to tripping defined as when CoM moves anterior and crosses the frontal boundary, the line between the stance toe and swing toe. CoM has constant anterior velocity and the limb swing motion stops if the swing foot contacts a fixed object, a "trip". As a result, CoM continues anterior progression and eventually reaches the anterior boundary, defined as initiation of anterior balance loss.

Tripping at MFC generates impact force, estimated by foot segment mass and acceleration. Based on the inverted pendulum model to describe CoM and swing phase lower limbs' movements [19], the equal amount of impact force due to tripping can be assumed to work on CoM. The two primary aims of the current study were to establish an available response time (ART) computational method due to tripping at MFC and identifying factors that influence ART.

II. Methods

A. Participants

The participants included 15 young male adults (18-35 yrs.) with physical characteristics: height 1.77 ± .06m, mass 73.6 ± 8.9kg, pelvis segment mass 10.5 ± 1.3kg, foot segment mass 1.6 ± 2.2kg). Two subjects were classified as left limb-dominant, determined by the established procedure [20]. All participants provided informed consent using procedures approved and mandated by the Victoria University Human Research Ethics Committee.

B. Protocol

Gait testing was conducted in an unconstrained laboratory environment without any gait disturbance (e.g. tripping), in

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which participants walked straight at preferred speed along an 8m walkway, comprising 60-90 gait cycles per subject from both limbs. Both heels and toes in addition to estimated CoM based on the pelvis segment [18], [21] were sampled by three Optotrak (Optotrak®, NDI, Canada) cameras at 100Hz. Pelvis segment CoM was based on the dynamic locations of anterior superior iliac crests, posterior inferior iliac spines and greater trochanters, modeled by the Visual 3D conventions.

C. *Event Definitions*

MFC was identified as the local minimum of the vertical height of the swing toe during the mid-swing phase [12], [22]. Horizontal acceleration and velocity of the swing toe, anterior and sideway (medio-lateral) CoM velocity, and x-y coordinates in the transverse plane of both swing and stance toes relative to CoM (0, 0) were obtained at MFC for balance loss simulation. In medio-lateral axis (x), the direction toward the dominant limb is positive (> 0) and in the anterior-posterior direction, the anterior direction (y) is positive (> 0).

D. *Computation Method*

ART computation method for anterior balance loss takes two steps including 1) sagittal simulation to obtain anterior acceleration on CoM due to tripping and 2) transverse simulation to compute ART for CoM to reach the frontal boundary. Anterior balance loss due to tripping at MFC starts with obtaining foot segment mass and horizontal swing toe acceleration data at MFC to compute impact force the swing foot would receive in case of tripping.

$$F(f) = A(f) \times M(f) \tag{1}$$

[F(f) = reaction force working on swing toe due to tripping; A(f) = acceleration working on swing toe; M(f) = mass of foot segment]

Following the equations below using the conventions of torque, the amount of impact force is considered to be equal to anterior force working on pelvis CoM (Fig. 1, top).

$$T = F(f) \times \sin(\theta) \times l = -F(c) \times \sin(\theta) \times l \tag{2}$$

$$F(f) = -F(c) \tag{3}$$

$$A(c) = -F(f)/M(c) \tag{4}$$

[T = torque due to tripping; F(c) = force working on CoM due to tripping; A(c) = acceleration working on CoM due to tripping; M(c) = mass of pelvis segment]

Followed, transverse plane simulation aimed to divide distance to balance loss by overall average velocity of CoM from the current (0, 0) location to the balance loss point (Fig. 1, bottom). Balance loss point is the intersection between the two lines: transverse CoM trajectory and the anterior boundary. The coordinate of Balance loss point (X, Y), distance to balance loss (D) and ART (t) can be expressed in the following equations.

Balance loss point's coordinate (X, Y);

$$X = \left[Ry - \frac{Rx(Ry-Ly)}{Rx-Lx}\right] / \left[\frac{V(cy)}{V(cx)} - \frac{Ry-Ly}{Rx-Lx}\right] \tag{5}$$

$$Y = \frac{V(cy)}{V(cx)} \times \left[Ry - \frac{Rx(Ry-Ly)}{Rx-Lx}\right] / \left[\frac{V(cy)}{V(cx)} - \frac{Ry-Ly}{Rx-Lx}\right] \tag{6}$$

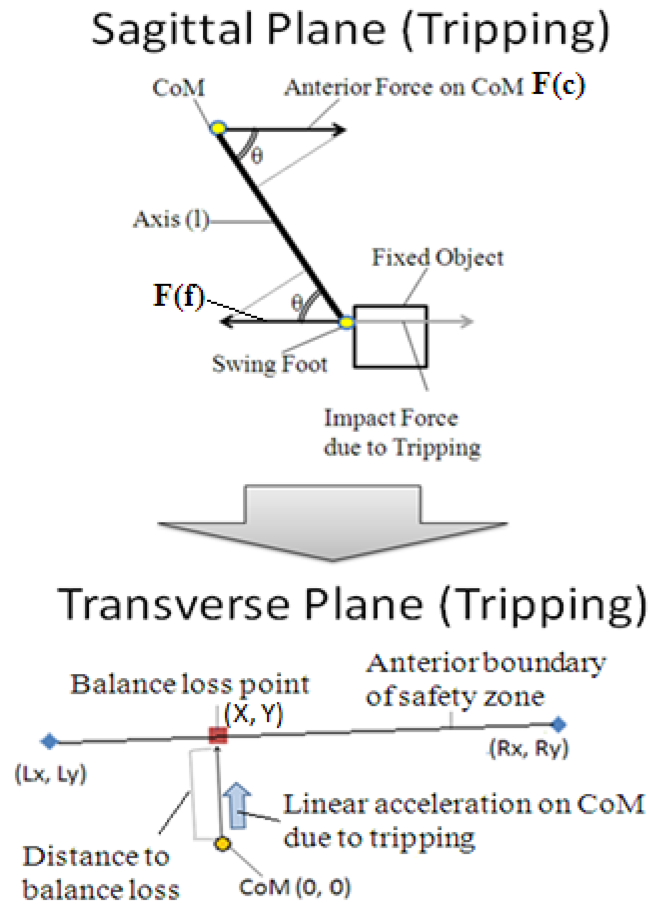

Figure 1 (Top) Illustration of force transfer from the tripped swing foot to pelvis CoM. (Bottom) Illustration of ART calculation in transverse plane. Right/left toe coordinates (Rx, Ry; Lx, Ly).

Distance to balance loss (D);

$$D = \sqrt{X^2 + Y^2} \tag{7}$$

ART (t);

$$t = \frac{-V(c) + \sqrt{V(c)^2 + 2 \times A(c) \times D}}{A(c)} \tag{8}$$

[R(x, y) = right foot coordinate; L(x, y) = left foot coordinate; V(cx, cy) = velocity of CoM (x, y)]

E. *Statistical Analysis*

Limb effects were analyzed for all the examined parameters: MFC toe acceleration, MFC toe velocity, medio-lateral CoM velocity, anterior CoM velocity, (x, y) swing and stance toe coordinates, tripping force, momentum on tripped foot, time of tripping force, linear acceleration on CoM due to tripping, distance to balance loss and ART. Pearson's correlation analysis was also performed for any interdependency between all the parameters above. P-values lower than .05 was accepted as statistically significant.

III. Results

Both obtained data and computed data are summarized in Table 1 below. No limb effect was obtained for any of the parameters.

TABLE I. RESULTS OF OBTAINED DATA AND COMPUTED DATA

Obtained Data	Dominant	Non-dominant
MFC toe acceleration (m/s²)	0.45 ± 0.94	0.48 ± 1.04
MFC toe velocity (m/s)	4.66 ± 0.17	4.68 ± 0.17
ML CoM velocity (m/s)	-0.01 ± 0.03	0.01 ± 0.03
Anterior CoM velocity (m/s)	1.17 ± 0.06	1.15 ± 0.06
X-swing toe (m)	0.12 ± 0.01	-0.13 ± 0.01
Y-swing toe (m)	0.13 ± 0.02	0.12 ± 0.02
X-stance toe (m)	0.06 ± 0.01	-0.06 ± 0.01
Y-stance toe (m)	0.12 ± 0.01	0.13 ± 0.01
Computed Data	**Dominant**	**Non-dominant**
Tripping force (N)	1.24 ± 3.40	1.89 ± 5.58
Momentum on tripped foot (kg.m/s)	7.33 ± 8.70	7.25 ± 8.29
Time of tripping force (s)	6.86 ± 5.61	8.40 ± 11.04
Linear acceleration on CoM due to tripping (m/s²)	0.11 ± 0.28	0.15 ± 0.45
Distance to balance loss (m)	0.13 ± 0.03	0.12 ± 0.03
ART (s)	0.11 ± 0.03	0.11 ± 0.03

Results of correlation analysis between ART and the other parameters are displayed in Fig. 2. Significant correlations indicate that gait data adaptations at MFC to achieve longer ART were directly associated with more anterior stance toe location, more lateral swing toe location, greater distance to the anterior boundary, lower anterior CoM velocity and lower toe velocity. Further correlation analysis confirmed that these adaptations were interlinked with each other. More anterior stance toe is positively correlated with greater distance to the anterior boundary ($r = .484$, $p < .05$). More lateral swing toe is in association with lower MFC toe velocity ($r = -.444$, $p < .05$) and anterior CoM velocity ($r = -.429$, $p < .05$) as indicated by significant negative correlations. Reduction in MFC toe velocity is accompanied with shorter time of tripping force ($r = .586$, $< .01$), slower anterior CoM velocity ($r = .946$, $p < .01$) and more lateral swing toe location ($r = -.444$, $p < .05$).

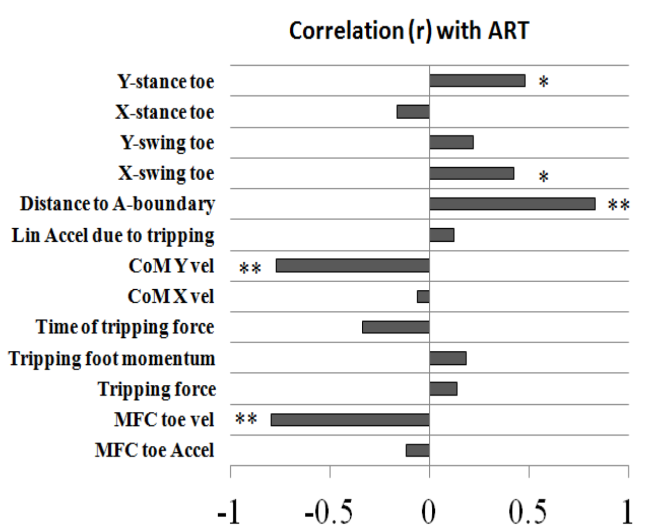

Figure 2. Correlation between ART and examined parameters. Abbreviations: Y- = anterior-posterior, X- = medio-lateral, A- = anterior, Lin = linear, Accel = acceleration, vel = velocity. Significant effects * ($p < .05$) and **($p < .01$).

IV. DISCUSSION

Understanding tripping biomechanics is important in understanding falls and the development of the MFC-tripping concept has greatly advanced the study of ageing-associated tripping risk [12-15]. Previous MFC examinations have, however, mainly focused on frequency of tripping with limited research attention to characterize severity of tripping-associated anterior balance loss based on gait characteristics at MFC. ART computation and associated kinetic descriptions, including force or momentum of impact due to tripping at MFC were expected to assess the difficulty of recovery from tripping.

On average, 0.11s has been identified as ART due to tripping-associated anterior balance loss regardless of limb dominance. Based on correlation analysis in Fig. 2, the five critical factors to prolong ART were identified as 1) anterior stance toe, 2) lateral swing toe, 3) increase in distance to the anterior boundary, 4) reduction in anterior CoM velocity and 5) reduction in toe velocity at MFC. Interestingly, toe acceleration and simulated force working on swing toe in case of tripping were not correlated with ART.

Assuming the stance foot was fixed on the walking surface, more posterior CoM at MFC with respect to the *lead* stance foot could be the adaptation to attain the 'relatively' anterior stance foot location. Having MFC earlier in the swing phase before CoM is approaching the *lead* stance foot could possibly assist this adaptation. The relatively more anterior stance toe was also useful in lengthening distance to the anterior boundary of supporting base, which prolongs ART as indicated by significantly positive correlation.

Taking more lateral swing toe trajectory was revealed advantageous in directly and indirectly increasing ART. Such an effect can be considered most easily attained by 'toeing-out' swing foot rather than intentionally controlling the entire swing foot to take the more lateral path. Toeing-out is also effective in reducing anterior velocity of both CoM and swing toe where slowing down was identified effective in extending ART. Although slower gait may benefit at MFC, it is important to note that recovery from anterior heel slipping after heel contact will become more difficult if CoM anterior velocity reduces [23], and accordingly, recommending 'slower gait' as safety adaptation needs careful consideration.

Standard deviation shown in Table 1 suggests that ART computation should be treated qualitatively due to the high variability in some parameters. For example, toe acceleration at MFC was found to be negative (< 0) in some trials and in such case, tripping force also becomes negative while momentum measure constantly indicates positive due to the consistent anterior movement of the swing toe. While the calculation was based on the average of all the obtained data, it may not be adequate to use this ART computation method if toe anterior velocity was decelerating at MFC. The alternative method to calculate reaction forces could be therefore possible by first *estimating* 'time of reaction forces working on a tripped foot' (time of tripping force in Table 1) despite the difficulty in making a reasonable assumption. Another limitation of the established computation method is directly linked to the human gait description by the inverted pendulum model [19]. Despite its predominance in explaining human gait [24], the inverted pendulum model is based on the assumption that the lower limb is one rigid segment and knee joint kinematics is not considered. Although subtle knee joint motion may not critically affect this gait model, knee joint mechanics may influence the result of ART computation to a small degree. Yet, this notion is rather in relation to the model of human walking and may not be the central focus of the anterior balance loss simulation.

The principle of ART computation is similar to extrapolated centre of mass [17], [24] in characterizing dynamic CoM movement by position and velocity. Extrapolated centre of mass is particularly useful in describing balance with respect to centre of pressure (CoP) therefore stance foot, while ART computation is based on the CoM movement toward the anterior boundary at MFC (Fig. 1, bottom). The current ART computation method for tripping accounts for the time limit for anterior balance loss without any recovery action taken. Previous studies [25], [26], however, reported the essential contribution of the stance limb push-off task in providing additional ART when tripping. In future research, it will therefore be interesting to incorporate the stance limb's push-off role to investigate ART mechanism more in detail. Application of the currently established ART computation method into gait of older adults is the certain direction of research to further examine how ageing increases the risk of tripping falls.

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REFERENCES

[1] T.A. Soriano, L.V. DeCherrie, and D.C. Thomas, "Falls in the community-dwelling older adult: A review for primary-care providers." *Clinical Interventions in Aging*, 2(4), 2007, pp. 545-553.

[2] J.A. Stevens, P.S. Corso, E.A. Finkelstein, and T.R. Miller, "The costs of fatal and non-fatal falls among older adults." *Injury Prevention*, 12, 2006, pp. 290-295.

[3] K. Hill, J. Schwarz, L. Flicker, and S. Carroll, "Falls among healthy, community-dwelling older women: a prospective study of frequency, circumstances, consequences and prediction accuracy." *Australian and New Zealand Journal of Public Health*, 23, 1999, pp. 41-48.

[4] D. Keskin, P. Borman, M. Ersöz, A. Kurtaran, H. Bodur, and M. Akyüz, "The risk factors related to falling in elderly females." *Geriatric Nursing*, 29, 2008, pp. 58-63.

[5] P.A. Stalenhoef, J.P.M. Diederiks, J.A. Knottnerus, A.D.M. Kester, and H.F.J.M. Crebolder, "A risk model for the prediction of recurrent falls in community-dwelling elderly: A prospective cohort study." *Journal of Clinical Epidemiology*, 55, 2002, pp. 1088-1094.

[6] Ministry of Internal Affairs and Communications, Statistics Bureau, Director-General for Policy Planning and Statistical Research and Training Institute, Japan. 2013. Available from <http://www.stat.go.jp/english/index.htm >

[7] T. Hayashi, "Falls prevention for older adults," *Japanese Journal of Geriatrics*, 44, 2007, pp. 591-594.

[8] W. Kakuda, and M. Abo, "Preventing falls: current status of falls and the preparedness action plan." *Tokyo Jikeikai medical Journal*, 123, 2008, 347-371.

[9] A.J. Blake, K. Morgan, M.J. Bendall, H. Dallosso, S.B.J. Ebrahim, T.H.D. Arie, P.H. Fentem, and E.J. Bassey, "Falls by elderly people at home prevalence and associated factors. *Age and Ageing*, 17, 1988, pp. 365-372.

[10] F. Prince, H. Corriveau, R. Hebert, and D.A. Winter, "Gait in the elderly." *Gait and Posture*, 5, 1997, pp. 128-135.

[11] C. Smeesters, W.C. Hayes, and T.A. McMahon, "Disturbance type and gait speed affect fall direction and impact location." *Journal of Biomechanics*, 34, 2001, pp. 309-317.

[12] H. Nagano, R.K. Begg, W.A. Sparrow, and S. Taylor, "Ageing and limb dominance effects on foot-ground clearance during treadmill and overground walking." *Clinical Biomechanics*, 26(9), 2011, pp. 962-968.

[13] R. Begg, R. Best, L. Dell'Oro, and S. Taylor, "Minimum foot clearance during walking: Strategies for the minimization of trip-related falls." *Gait and posture*, 25, 2007, pp. 191-198.

[14] W.A. Sparrow, R.K. Begg, and S. Parker, "Variability in the foot-ground clearance and step timing of young and older men during single-task and dual-task treadmill walking." *Gait and Posture*, 28, 2008, 563-567.

[15] D.A. Winter, "The biomechanics and motor control of human gait: normal elderly and pathological 2nd edition." *Waterloo Biomechanics*.

[16] A.E. Patla, S.D. Prentice, C. Robinson, C, and J. Neufeld, "Visual control of locomotion: strategies for changing direction and for going over obstacles. " *Journal of Experimental Psychology*, 17 (3), 1991, pp. 603-634.

[17] A.L. Hof, M.G.J. Gazendam, and W.E. Sinke, "The condition for dynamic stability." *Journal of Biomechanics*, 38, 2005, pp. 1-8.

[18] H.J. Lee, and L.S. Chou, "Detection of gait: instability using the centre of mass and centre of pressure inclination angles." *Archives of Physical Medicine and Rehabilitation*, 87 (4), 2006, pp. 569-575.

[19] A.D. Kuo, "The six determinants of gait and the inverted pendulum analogy: A dynamic walking perspective." *Human Movement Science*, 26, 2007, pp. 617-656.

[20] M.K. Seeley, B.R. Umberger, and R. Shapiro, "A test of the functional asymmetry hypothesis in walking." Gait & Posture, 28, 2008, pp. 24-28.

[21] E.M. Gutierrez-Farewik, A. Bartonek, and H. Saraste, H, "Comparison and evaluation of two common methods to measure center of mass displacement in three dimensions during gait." *Human Movement Science*, 25, 2006, pp. 238-256.

[22] C.M. O'Connor, S.K. Thorpe, M.J. O'Malley, and C.L. Vaughan, "Automatic detection of gait events using kinematic data." *Gait and Posture*, 25, 2007, pp. 469-474.

[23] J.Y. You, Y.L. Chou, C.J. Lin, and F.C. Su, "Effect of slip on movement of body center of mass relative to base of support." *Clinical Biomechanics*, 16, 2001, pp. 167-173.

[24] A.L. Hof. "The 'extrapolated centre of mass' concept suggests a simple control of balance in walking. *Human Movement Science*, 27, 2008, pp. 112-125."

[25] M. Pijnappels, N.D. Reeves, C.N. Maganaris, and J.H. van Dieen, "Tripping without falling: lower limb strength, a limitation for balance recovery and a target for training in the elderly." *Journal of Electromyography and Kinesiology*, 18, 2008, pp. 188-196.

[26] M. Pijnappels, M.F. Bobbert, and J.H. van Dieen, "Push-off reactions in recovery after tripping discriminate young subjects." *Gait and Posture*, 21, 2005, pp. 388-394.