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CAN SACRAL MARKER APPROXIMATE CENTER OF MASS DURING GAIT AND SLIP-FALL RECOVERY AMONG COMMUNITY-DWELLING OLDER ADULTS?

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ABSTRACT

Falls are prevalent in older adults. Dynamic stability of body center of mass (COM) is critical for maintaining balance. A simple yet accurate tool to evaluate COM kinematics is essential to examine the COM stability. The purpose of this study was to determine the extent to which the COM position derived from body segmental analysis can be approximated by a single (sacral) marker during unperturbed (regular walking) and perturbed (gait-slip) gait. One hundred eighty seven older adults experienced an unexpected slip after approximately 10 regular walking trials. Two trials, the slip trial and the preceding regular walking trial, monitored with a motion capture system and force plates, were included in the present study. The COM positions were calculated by using the segmental analysis method wherein, the COM of all body segments was calculated to further estimate the body COM position. These body COM positions were then compared with those of the sacral marker placed at the second sacral vertebra for both trials. Results revealed that the COM positions were highly correlated with those of the sacrum's over the time intervals investigated for both walking (coefficient of correlation $R > 0.97$) and slip ($R > 0.90$) trials. There were detectable kinematic difference between the COM and the sacral for both trials. Our results indicated that the sacral marker can be used as a simple approximation of body COM for regular walking, and to somewhat a lesser extent, upon a slip. The benefits from the simplicity appear to overweigh the limitations in accuracy.

Keywords: Falls prevention, Slip, Skin-surface marker, Gait analysis

INTRODUCTION

Falls are a major health concern faced by older adults worldwide (Tinetti, 2003). Slip-related falls account for about 40% of outdoor falls among older adults (Luukinen et al., 2000). Poor balance and consequently mobility restrictions are limiting factors in a person's health, confidence, ability to perform activities of daily living, and overall quality of life (Rubenstein and Josephson, 2002). These factors are serious problems that many older adults and people with neurological and muscular-skeletal disorders experience in their day-to-day lives. Gait and balance disorders in older adults are specifically manifested in an impaired ability to compensate for stance/gait perturbations (Granacher et al., 2012). Thus, the ability to maintain balance becomes an important aspect to prevent falls and to assess the effect of gait training.

Falls monitoring or detection for everyday living at home, which may provide invaluable information for formulating effective reduction strategies, has attracted growing attention (Aziz and Robinovitch, 2011; Bianchi et al., 2010; Nyan et al., 2008). The dynamic stability of the center of mass (COM) has been proven as a critical factor resulting in slip-related falls among both young and old adults during daily activities like gait (Pai and Bhatt, 2007; Yang et al., 2009) or sit-to-stand (Pavol and Pai, 2007). The stability is characterized as the dynamic relationship of the motion state (i.e. the position and velocity) of COM related to its base of support (BOS) during movement (Pai, 2003). Therefore, monitoring the motion of the body COM in daily living can be an important part of the home monitoring program.

Traditionally, the COM position is computed by using the segmental analysis method, in which the kinematics of a large set of markers placed at the essential body segments are needed (Thirunarayan et al., 1996). These markers' positions are usually recorded by the motion capture systems. While this method has often been considered a gold standard in the COM calculation (Eng and Winter, 1993), its measurement is expensive and time-consuming and is nearly impossible to apply in any everyday living monitoring program.

Alternatively, it has been proposed that the COM as an imaginary point is often located anterior to the second sacral vertebra, at 55% of body height during standing among able-bodied adults (Saunders et al., 1953). Therefore, it is possible to use the position of sacrum to approximate the entire body's COM position during movement. This approximation has been examined in the vertical direction during gait among healthy adults (Gard et al., 2004) and patients (Thirunarayan et al., 1996). Though earlier results indicate that the sacral marker can substitute the body COM reasonably well in the vertical direction (Gard et al., 2004; Thirunarayan et al., 1996), it is still unclear whether and to what extent it could also represent the COM position in other two directions during regular walking. A tilted pelvis and continuously-changing body mass distribution from swinging limbs during walk can affect the relative position of the COM and the sacrum (Murray et al., 1964). It remains unknown whether such bias can be tolerated and a single sensor place in that region could still provide reasonable approximation of the COM motion.

The purpose of this study was to determine the extent to which the COM position derived from body segmental analysis can be approximated by a single (sacral) marker during unperturbed (regular walking), perturbed (gait-slip) gait, and fall recovery among community-dwelling older adults. We expected that the displacement of the sacral marker would present a high degree of correlation with that of the COM over these people's entire gait cycle upon both regular walking and gait-slip.

METHODS

2.1 Subjects

One hundred eighty seven healthy older adults (age: 71.9 ± 5.1 years; body mass 76.4 ± 13.8 kg; body height 1.66 ± 0.09 m; 129 females) participated in the study. All subjects gave a written informed consent to the experimental protocol approved by the Institutional Review Board. They were well informed about the experimental procedures and the purpose of the study. All participants were free of musculoskeletal, neurologic, cardiopulmonary, and other systemic disorders as assessed through a questionnaire.

2.2 Experimental setup

All participants walked on a 7-m walkway in which a sliding device was embedded during the experiment. The device consisted of a side-by-side pair of low-friction, passively movable platforms each mounted upon a metal frame supported by two individual force plates (AMTI, Newton, MA) in order to record the ground reaction force (Yang and Pai, 2007). The platforms were free to slide up to > 0.75 m forward upon a computer-controlled release of their locking mechanisms. A harness, connected by shock-absorbing ropes at the shoulders and waist to an overhead beam, was employed to protect subjects while imposing negligible constraint to their movement (Yang and Pai, 2011). A load cell measured the force exerted on the ropes. Full body kinematic data from 26 retro-reflective markers placed on the subjects' body were gathered using an 8-camera motion capture system (MAC, Santa Rosa, CA) synchronized with the force plates. Specifically, these 26 markers were affixed at vertex, ears, rear neck (the spinous process of the seventh cervical vertebra), shoulders (the acromion of the scapulae), midpoint of the right scapula, elbows (the lateral humeral epicondyles), wrists (the radial styloid processes), sacral (the second sacrum vertebra), greater trochanters, mid-thighs, knees (the lateral femoral epicondyles), mid-legs (the tibial tubercles), ankles (the lateral malleoli), heels (calcaneal tuberosities), and the fifth metatarsal heads.

Subjects were informed that they would be performing normal walking initially and would experience simulated slip later without knowing when, where, and how that would happen. They were only told to try to recover their balance on any slip incidence and then to continue walking. After about 10 regular walking trials, the right platform was always firstly released when right foot contacts it. The left platform would then be released once subjects landed left foot on it during the slip trial.

2.3 Data analysis

For each subject, the slip trial and the regular walking trial immediately prior to the slip were analyzed. Marker displacement data were low-pass filtered at marker-specific cut-off frequencies (range 4.5-9 Hz) using fourth-order Butterworth filters (Winter, 2005). Locations of joint centers, heels, and toes were computed from the filtered marker positions. For the segmental analysis method, the COM displacement was computed using gender-dependent segmental anthropometric parameters (de Leva, 1996) based on a 13-segment body human model and the calculated joint centers in all three directions: anteroposterior (X, positive: forward), mediolateral (Y, positive: leftward), and vertical (Z, positive: upward). The calculated COM positions would be compared with the ones of the sacral marker. The position of both the COM and sacral marker would be referenced to the position of right heel at its touchdown.

For a regular walking or a slip trial in which subjects did not fall, four characteristic gait events in an entire gait cycle, including right foot touchdown (RTD), left foot liftoff (LLO), left foot touchdown (LTD), and right foot liftoff (RLO) were identified from the vertical component of the ground reaction force. A vertical force greater than 10N corresponded to touchdown of that foot; descent below 10 N corresponded to liftoff (Ghoussayni et al., 2004). For a slip trial in which the subject fell (i.e. the peak load cell force during slip exceeded 30% of body weight) (Yang and Pai, 2011), the events of RTD, LLO, and RLO as well as the instant of fall were identified. The instant of fall was determined as the time when the load cell force exceeded 30% of body weight (Yang and Pai, 2011).

2.4 Statistics

The displacement trajectories over the entire gait cycle from RTD to next RTD (for regular walking or slip-recovery trial) or from RTD to the instant of fall (for slip-fall trial) from the sacral marker and from the COM were compared by computing their coefficient of correlation (*R*) and root-mean-square (RMS) error. The coefficient of correlation estimates how similar the trajectory shapes are between COM and sacral marker – higher the value greater similarity the two are. The RMS error quantifies the overall difference of the trajectories of COM and sacral marker over a time period. The paired *t*-tests were then used to examine if the COM position was different from or similar to the one of the sacral marker on all three directions at all four events for both normal walking and slip trials. The linear correlation between sacrum position and COM position were derived by conducting a linear fitting of these two measurements over all four gait events. All statistics were performed using SPSS 19.0 (IBM Corp., Armonk NY), and a significance level of 0.05 was used throughout.

RESULTS

Of 187 slip trials, falls occurred in 98 of them. The time history of the displacement of the sacral marker and the COM calculated from segmental analysis method in all three directions were fundamentally similar in appearance during both the regular gait and slip trials (Fig. 1, Table 1), as evidenced by the high correlation between them. Specifically, upon the normal walking trials, the coefficients of correlation between the COM and sacral marker in X (anteroposterior), Y (mediolateral), and Z (vertical) directions were respectively 0.999 ± 0.001, 0.983 ± 0.025, and 0.975 ± 0.028. The coefficients of correlation were 0.999 ± 0.001, 0.978 ± 0.046, and 0.902 ± 0.154 for three directions on the slip trials (Table 1).

Though the shape was closely similar between the COM and the sacral marker displacements, there were noticeable differences between them. For instance, the smallest RMS between the COM and the sacral marker displacement among three directions occurred in the Y direction for both regular gait (0.018 ± 0.011 m) and slip (0.024 ± 0.022 m) trials. While in the X direction, the RMS was the greatest one among three directions for both normal walking (0.168 ± 0.024 m) and slipping (0.173 ± 0.025 m) trials (Table 1).

For all four gait events, paired *t*-test results indicated that the sacral marker was significantly more posterior as well as lower than the COM in X and Z directions upon both normal gait and slip trials (Table 2, $p < 0.001$ for all; Table 3). In the Y direction, the position of the COM was significantly different from the sacral marker position at LLO and LTD upon the normal regular gait, and at LLO, LTD, and RLO (or fall) on slip trials ($p < 0.001$ for all, Table 2; Table 3). In the Y direction, the position of the COM was significantly different from the sacral marker position at LLO and LTD upon the normal regular gait, and at LLO, LTD, and RLO (or fall) on slip trials ($p < 0.001$ for all, Table 2; Table 3).

Upon both regular gait and slip trials, the COM position was linearly correlated to the sacral marker position at all four gait events. For the normal walking trials, the coefficients of correlation between the COM and the sacral marker across all four gait events in the directions of X, Y, and Z respectively were 0.997, 0.860, and 0.836 (Fig. 2, $p < 0.001$ for all). These values became 0.992, 0.849, and 0.893 for the three directions across all four events on the slip trials (Fig. 3, $p < 0.001$ for all)

DISCUSSION

The results of the present study indicated that there are very strong (*R* > 0.99) correlative relation between the sacral marker and the body COM in anteroposterior direction during both the regular gait, slip, and fall recovery, such that the differences between the two can simply be reduced or eliminated by an offset anterior shift of the former by 0.17 m to reasonably approximate the latter. In comparison, the correlations in the other two directions are almost as strong as that in anteroposterior direction. In the vertical direction, there is a need of upward shifting the former by about 0.02 – 0.05 m (Tables 1 and 3). Though the differences in mediolateral direction is the smallest (i.e., the RMS = ~0.02 m, Table 1), it is also the most difficult to correct such differences due to the lack of a consistent trend throughout the entire gait cycle.

The results supported our hypothesis that the kinematics of the sacral marker highly correlates with that of the COM which is calculated using the segmental analysis method over an entire gait cycle upon both regular walking and gait-slip. Specifically, the coefficients of correlation between sacral marker and the COM trajectory were > 0.97 for regular gait trials and > 0.89 for slip trials. The finding of the high correlation between sacral marker and the COM position upon normal walking was consistent with the results reported previously, like 0.94 (Floor-Westerdijk et al., 2012) and 0.78 (Gard et al., 2004), suggesting that the sacral marker and the COM move in the similar waveform during walking and slipping.

However, the absolute differences between these two measurements were still detectable in all three directions upon both normal and slip trials (Tables 2 and 3). The differences of the anteroposteiror, mediolateral, and vertical displacement between the sacral marker and COM across the entire gait cycle were respectively 0.17 m, 0.02 m, and 0.03 m upon the normal walking. The greatest difference occurred in the anteroposteiror direction. Such discrepancy could be contributed to the assumption that the COM can be closely approximated by the motion of a single marker. Actually, the COM is an imaginary point inside the pelvis during walking. Previous study has proposed that the center of the pelvis, defined as the centroid of the triangle from the left anterior superior iliac spine, the right anterior superior iliac spine, and the mid-point of the two posterior superior iliac spines, could approximate the COM during walking (Eames et al., 1999). In the present study, the sacral marker was placed to the second sacral vertebra. The offset between the pelvis centroid and the second sacral vertebra was about 0.195 m (Floor-Westerdijk et al., 2012), which was very close to the RMS value (0.17 m) calculated in the present study in the anteroposteiror direction in the normal walking trials (Table 1).

The differences in the position between the sacral maker and the COM in other two directions (mediolateral and vertical) could be resulted from several sources. First, the COM is an imaginary point at which the total body mass can be assumed to be concentrated and thus affected by the movement of all body segments. Therefore, it is not a fixed point although its movement excursion in mediolateral or vertical direction is relatively small (around 0.03 m in both directions) (Gard et al., 2004; Gutierrez-Farewik et al., 2006). Any movement of a body segment would theoretically move the true body COM with respect to the sacral marker during walking. When movements of the trunk, head, and upper extremities increase, the accuracy of the estimation of the COM from the sacral marker will decrease (Gard et al., 2004; Gutierrez-Farewik et al., 2006; Whittle, 1997). Second, the pelvic rotations around all three axes could also be an attributor to the differences of displacement between sacral marker and body COM. As aforementioned, the anteroposteiror offset between the sacral marker and the COM is around 0.17 m. The pelvis rotates about 8º around the vertical axis (Saunders et al., 1953). Such pelvis rotation would solely cause the difference in mediolateral direction up to about 2.4 cm. Further, the tilt of the pelvis would also affect the relative position of the sacral marker to the COM during walking. Anteroposterior tilt of the pelvis during walking (Saunders et al., 1953) can introduce artificial vertical motion because of the offset between COM and sacral marker (Saini et al., 1998). Large anteroposterior tilt along with lateral tilt of the pelvis could change the vertical position of a skin-surface marker on the sacrum with respect to the COM position due to the out-of-plane rotations (Gard et al., 1996).

The results revealed that the differences of the sacral marker and the COM position were generally greater in slip trials than in regular gait, as evidenced by the lower coefficient of correlation and greater RMS for the slip trials (Tables 1 and 3). This could be explained by the significant trunk movement. Upon the first unannounced slip, all subjects experienced a backward balance loss and took a recovery step to regain body balance. The recovery process interrupted the regular gait pattern and further affected the trunk's movement. Significant trunk rotation on the sagittal plane has been observed among healthy older adults during gait-slip (Troy et al., 2008; Yang et al., 2012). The trunk rotation could reach up to 10º after slip onset (Yang et al., 2012), while the rotation magnitude during regular gait is only about 3º (Krebs et al., 1992). The great trunk movement during slip trial would change the mass distribution of the body; consequently alter the relative COM position to the sacral marker. Further, the changes in trunk movement would affect the pelvis's movement. Such changes thus resulted in the alteration of the relative position of the sacral marker and the COM, as mentioned above. Despite of the greater RMS and smaller coefficient of correlation in comparison to the regular gait, the slip trials still demonstrated high correlations ($R > 0.90$) between the sacral marker and the COM position (Table 1), indicating the similar appearance between the sacral marker and the COM displacement during slip trials.

While theoretically more precise, the segmental analysis method relies on full-body marker sets and involves many assumptions. Each segment of the human model used to apply segmental analysis method is assumed as a rigid linkage without considering the wobbling masses (Gunther et al., 2003), which may influence the true COM position. The use of Zatsiorsky equations and anthropometric data to compute the COM and mass of segments is based upon many approximations (de Leva, 1996). Inertial parameters of individual segments are based on cadaver limb segments and not on live tissue, which may differ in density characteristics. Such segmental inertial parameters based on anthropometric measurements may not accurately reflect the subjects' individual characteristic (Saini et al., 1998). These approximations and assumptions make it questionable how accurate the segmental analysis method estimates the COM displacement. Further, due to the expensive cost, time consuming in operation, and the restricted use in gait laboratories, the segmental analysis method is hard to be broadly employed in the clinical centers. Nowadays, much effort is being directed into finding ways for performing ambulant and continuous measurements outside gait laboratories. This study provides a potentially practical substitution of the segmental analysis method to measure the COM during human movements under both unperturbed and perturbed conditions.

At all four gait characteristic gait events upon both normal walking and slipping trials, the COM and the sacral marker could be linearly fitted with high accuracy (Figs. 2 and 3). To our best knowledge, this is the first study deriving the correlation equations between the sacral marker and the COM position for both unperturbed and perturbed trials. Such linear fittings provide us a simple yet accurate approach to calculate the COM from the sacral marker position during regular gait and slip. Because the sacral marker method simply involves tracking the position of the marker that was placed on sacrum as the subject walked, this method bears promising applications in clinics. For example, this method offers a simple and inexpensive way to assess the control of COM stability among older adults. It can be used as a biofeedback to train individuals with elevated risk of falls in improving their control of dynamic stability in gait. It could also be easily integrated into perturbation training or assessment where the immediate outcome-based feedback is needed for the treatment or training. Combined with inertial sensor placed on sacrum, this method could become an efficient tool in monitoring fall incidence in everyday life and performing ambulant and continuous measurements outside gait laboratory. It can be used to provide input to trigger the use of hip impact damping device. It may also be useful for product development, such as wearable sensors (Nyan et al., 2008) that can effectively and efficiently be deployed to trigger an air-bag-like device to reduce damage from the impact of a fall (Shi et al., 2009), hip protectors (Kannus et al., 2000), or safe floors (Casalena et al., 1998).

Our study has limitations. First, only “healthy” older adults were included in this study. It is unclear how these results may change with a different population (like individuals with movement disorders) even gait analysis is popularly used among those populations. Given the fact that falls are a serious health and social problem among even healthy older adults, this study still holds significant influence. Further, only four characteristic gait events within an entire gait cycle were chosen to examine the linear correlation between the sacral marker and the COM. While interpolation is a common practice to extract additional information, it remains unclear whether such linear relationship derived from these four events could represent other events in the gait cycle. Third, the segment inertial parameters used in this study did not completely take into account the subject variability (Chen et al., 2011) even the segment length was subject specific. This could introduce uncertain errors in COM estimate. Last, only displacement was involved in this study. It remains unclear whether the velocity and acceleration also resemble between COM and sacral marker. Given the high correlation between COM and sacrum displacement, we would expect both velocity and acceleration have good closeness. All these topics merit our further investigations.

Despite these limitations, this study investigated the accuracy of approximating the COM by using the sacral marker during both regular gait and slip based on a large sample size. It can be concluded that the simple method of measuring the sacral marker position could reasonably approximate the COM during both regular gait and slip. The derived linear relationship between the sacral marker and the COM provided us a simple but rather accurate approach to evaluate the COM upon both unperturbed and perturbed gait. This approach could be widely used in clinics to develop and evaluate fall prevention training paradigm, and to facilitate the technique of fall monitoring and detecting in everyday living (Bianchi et al., 2010), and to be integrated into the fast-developing wearable medical systems (Teng et al., 2008).

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CONFLICT OF INTEREST STATEMENT

None declared.

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TABLES

Table 1 Descriptive characteristics of the coefficients of correlation (*R*) and root-mean-square (RMS) error values between the COM and the sacral marker displacement in anteroposterior (X), mediolateral (Y) and vertical (Z) axes upon regular gait and slip trails for 187 older subjects. The characteristic variables included the mean, standard deviation, maximum, minimum, and median values.

	Direction	X		Y		Z	
Parameter	Index Type	Gait	Slip	Gait	Slip	Gait	Slip
R	Mean	0.999	0.999	0.983	0.978	0.975	0.902
	Standard deviation	0.001	0.001	0.025	0.046	0.028	0.154
	Maximum	1	1	1	0.999	0.999	0.999
	Minimum	0.999	0.983	0.838	0.634	0.813	0.412
	Median	1	0.999	0.993	0.993	0.984	0.976
RMS (m)	Mean	0.168	0.173	0.018	0.024	0.031	0.045
	Standard deviation	0.024	0.025	0.011	0.022	0.028	0.029
	Maximum	0.241	0.257	0.073	0.127	0.17	0.142
	Minimum	0.079	0.126	0.004	0.003	0.002	0.006
	Median	0.166	0.171	0.015	0.017	0.021	0.034

Table 2 Comparisons of the displacement in mean (SD) between body center of mass (COM) and sacral marker in three directions (anteroposterior: X; mediolateral: Y; and vertical: Z) at four gait characteristic events (right foot touchdown: RTD, left foot liftoff: LLO, left foot touchdown LTD, and right foot liftoff or the instant of fall) upon both regular gait and slip trials among 187 older adults. The position of both the COM and the sacral marker are referenced to the position of right heel at its touchdown.

	Direction	X (m)		Y (m)		Z (m)	
Trial	Events	COM	Sacral*	COM	Sacral	COM	Sacral*
Gait	RTD	-0.236(0.047)	-0.409(0.047)	0.098(0.028)	0.095(0.034)	0.916(0.053)	0.896(0.061)
	LLO	-0.046(0.041)	-0.210(0.042)	0.067(0.021)	0.056(0.028)*	0.927(0.053)	0.905(0.062)
	LTD	0.337(0.077)	0.169(0.086)	0.058(0.025)	0.049(0.029)*	0.917(0.052)	0.894(0.062)
	RLO	0.520(0.096)	0.362(0.103)	0.086(0.031)	0.085(0.034)	0.923(0.053)	0.904(0.060)
Slip	RTD	-0.235(0.049)	-0.409(0.048)	0.098(0.029)	0.097(0.034)	0.918(0.052)	0.897(0.062)
	LLO	-0.018(0.090)	-0.183(0.092)	0.063(0.028)	0.050(0.044)*	0.923(0.054)	0.906(0.065)
	LTD	0.112(0.105)	-0.068(0.111)	0.047(0.030)	0.033(0.046)*	0.915(0.061)	0.882(0.071)
	RLO$^{\Delta}$	0.299(0.149)	0.122(0.148)	0.019(0.044)	0.003(0.068)*	0.856(0.102)	0.798(0.102)

*: $p < 0.001$ vs. the COM calculated from segmental analysis method;

$^{\Delta}$: this event is the right liftoff (RLO) for slip-recovery trials; and the instant of fall for slip-fall trials.

Table 3 Descriptive characteristics of the differences of displacement between sacral marker and COM in three directions (anteroposterior: X; mediolateral: Y; and vertical: Z) at four gait events (right foot touchdown: RTD, left foot liftoff: LLO, left foot touchdown LTD, and right foot liftoff or the instant of fall) upon both regular gait and slip trials among 187 older adults. The characteristic variables included the mean, standard deviation, maximum, minimum, and median values.

	Index	Mean		Standard deviation		Maximum		Minimum		Median	
	Trial	Gait	Slip	Gait	Slip	Gait	Slip	Gait	Slip	Gait	Slip
Direction	Event										
X (m)	RTD	-0.173	-0.174	0.024	0.026	-0.086	-0.085	-0.246	-0.246	-0.170	-0.172
	LLO	-0.164	-0.165	0.025	0.026	-0.071	-0.078	-0.241	-0.239	-0.162	-0.163
	LTD	-0.167	-0.180	0.025	0.026	-0.084	-0.033	-0.238	-0.242	-0.166	-0.177
	RLO$^{\Delta}$	-0.159	-0.177	0.026	0.034	-0.077	-0.013	-0.242	-0.300	-0.157	-0.174
Y (m)	RTD	-0.003	-0.002	0.020	0.019	0.084	0.071	-0.062	-0.050	-0.003	-0.003
	LLO	-0.011	-0.010	0.019	0.019	0.071	0.037	-0.064	-0.063	-0.010	-0.010
	LTD	-0.008	-0.012	0.019	0.020	0.067	0.039	-0.057	-0.084	-0.009	-0.010
	RLO$^{\Delta}$	-0.001	-0.012	0.019	0.030	0.076	0.078	-0.047	-0.099	0.000	-0.010
Z (m)	RTD	-0.015	-0.018	0.027	0.028	0.073	0.036	-0.089	-0.096	-0.012	-0.014
	LLO	-0.018	-0.021	0.029	0.028	0.056	0.034	-0.099	-0.092	-0.015	-0.016
	LTD	-0.0167	-0.031	0.030	0.028	0.065	0.030	-0.097	-0.103	-0.013	-0.027
	RLO$^{\Delta}$	-0.023	-0.051	0.030	0.039	0.055	0.100	-0.102	-0.134	-0.020	-0.055

$^{\Delta}$: this event is the right liftoff (RLO) for slip-recovery trials; and the instant of fall for slip-fall trials.

CAPTIONS

Fig. 1 The a) anteroposterior (X, +: forward), b) mediolateral (Y, +: leftward), and c) vertical (Z, +: upward) displacement of the body center of mass (COM) calculated with the segmental analysis (solid line) and sacral marker (dashed line) methods for all 187 subject over a regular gait cycle, from right foot touchdown (RTD), through left foot liftoff (LLO), left foot touchdown (LTD), and right foot liftoff (RLO), to next RTD. The closeness between these two trajectories is evaluated by their coefficient of correlation (*R*) and root mean square (RMS). The position of both the body COM and sacral marker are referenced to the position of right heel at its first touchdown.

Fig. 2 The linear correlation between the body center of mass (COM) calculated with the segmental analysis method and the sacral marker in the directions of a) anteroposterior (X), b) mediolateral (Y), and c) vertical (Z) at four gait events including right foot touchdown (RTD), left foot liftoff (LLO), left foot touchdown (LTD), and right foot liftoff (RLO), during regular gait among 187 older subjects.

Fig. 3 The linear correlation between the body center of mass (COM) calculated with the segmental analysis method and the sacral marker in the directions of a) anteroposterior (X), b) mediolateral (Y), and c) vertical (Z) at four gait events including slipping (right) foot touchdown (RTD), left foot liftoff (LLO), left foot touchdown (LTD), and right foot liftoff (RLO for those who recovered) and the instant of fall when harness arrests 30% of body weight (Falls for fallers), during slip among 187 older subjects. RLO is used to denote both the instant of right foot liftoff and the instant of fall.

FIGURES

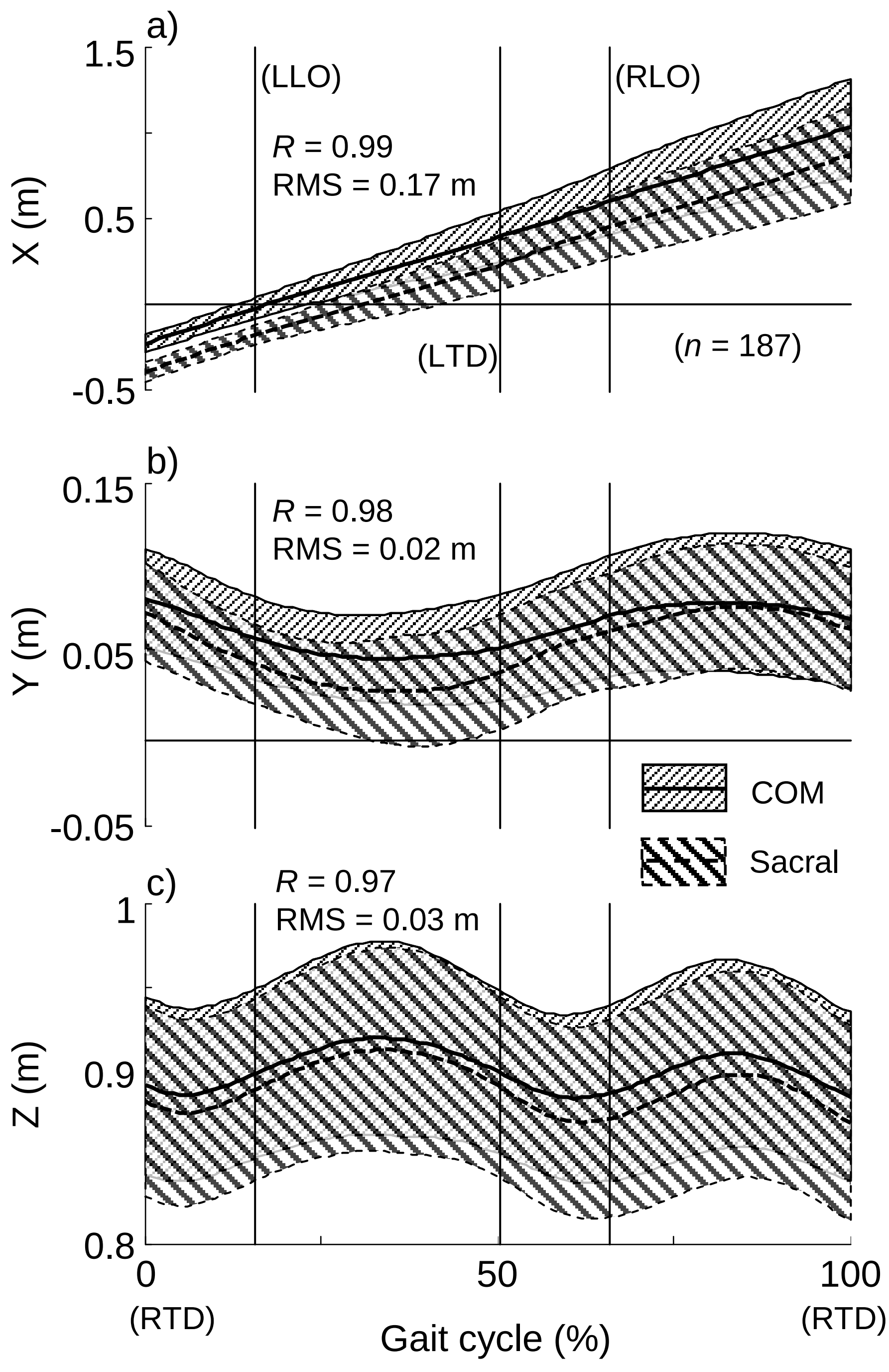

Fig. 1 [Yang & Pai, 2014]

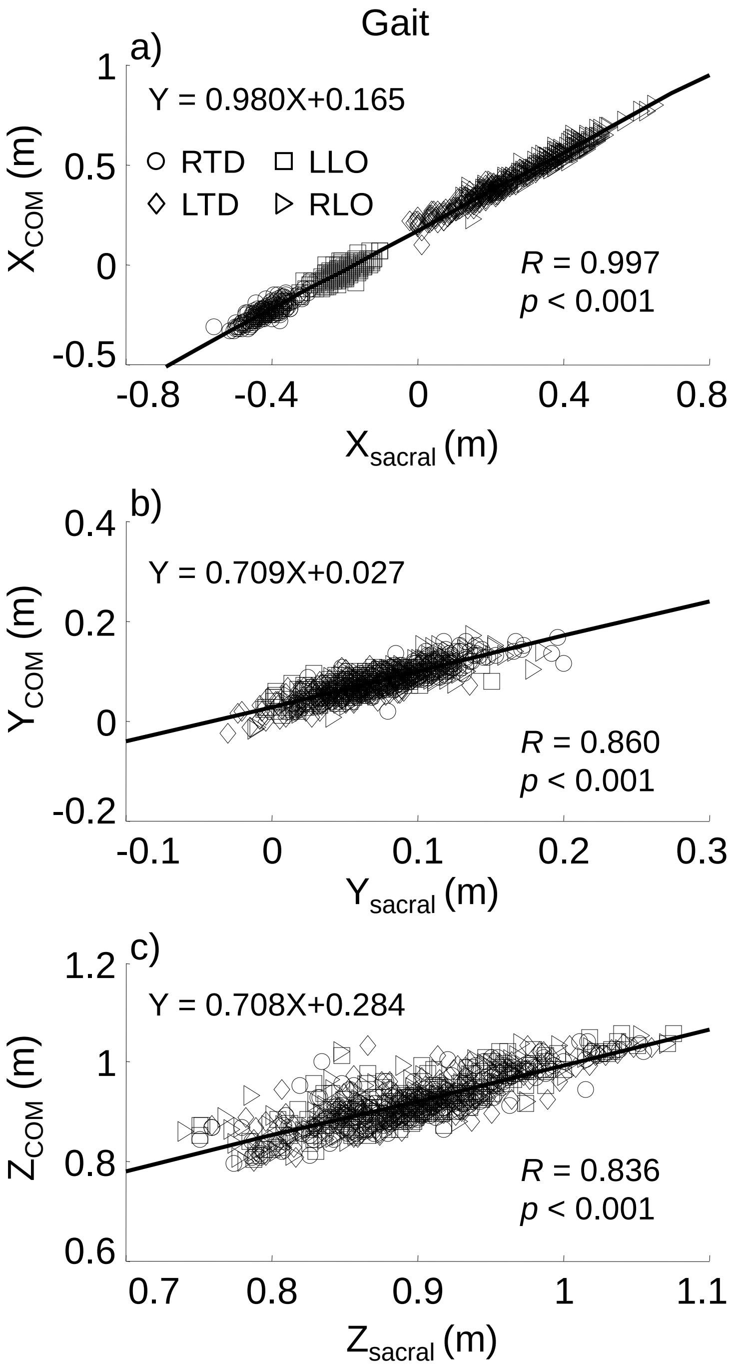

Fig. 2 [Yang & Pai, 2014]

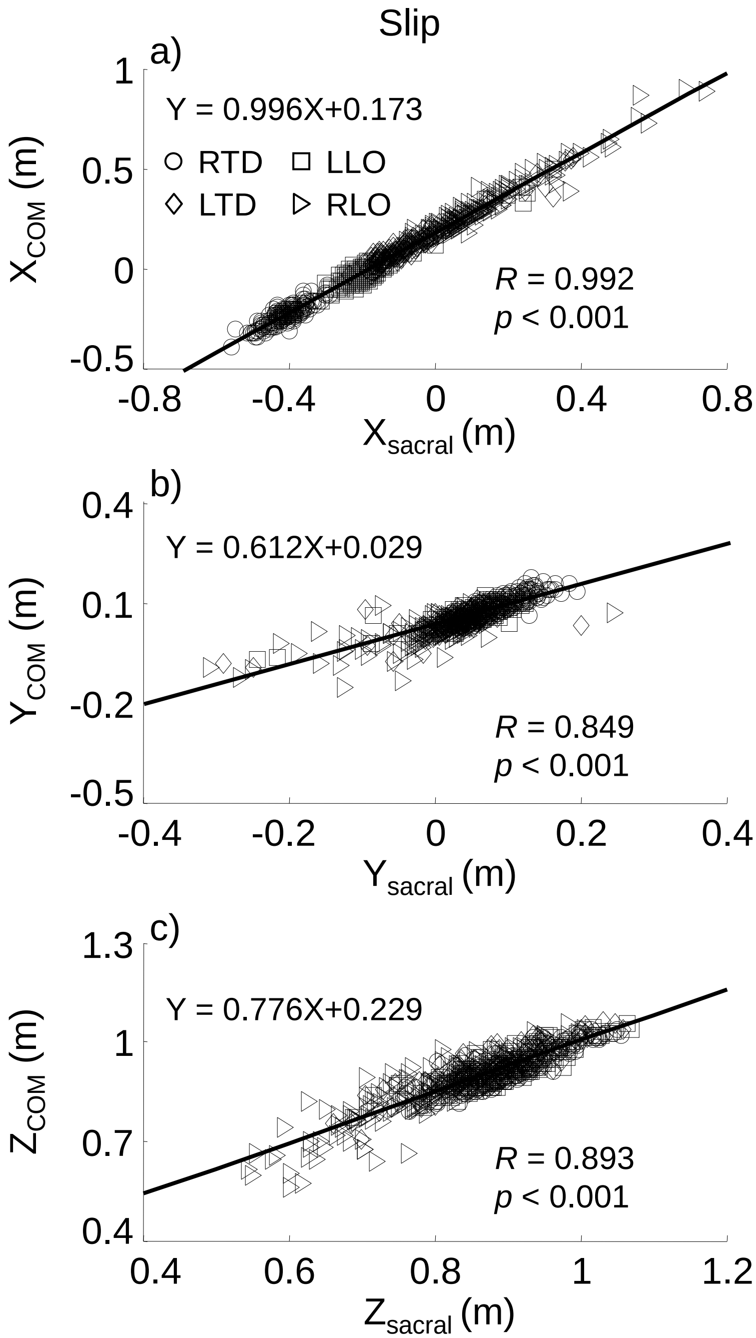

Fig. 3 [Yang & Pai, 2014]