Original Research

Abnormal Gait Movements Prior to a Near Fall in Individuals After Stroke

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Abstract *Objective:* To investigate the abnormal kinematic and kinetic movements in the last gait cycle before a near fall in individuals poststroke, where a near fall is defined as a physical therapist feeling the need to stabilize a patient.
Design: Retrospective study.
Setting: A rehabilitation center.
Participants: Twenty-five adults (22 men, 3 women; N=25) with an average age of 66.3 years and mean duration from stroke of 4 months who required manual assistance for a sudden imbalance during routine 3-dimensional motion analysis.
Interventions: Not applicable.
Main Outcome Measures: We compared the averaged usual gait cycle and the last cycle before the near-falling gait cycle (pre—near-falling gait cycle). We obtained the following spatiotemporal parameters: gait velocity, gait cycle duration, mediolateral center of mass displacement, step length, step width, joint moments, and angular displacement of the trunk in a cycle. Peak values of joint moments and trunk angle displacement were calculated.
Results: Etiology for near falls included toe trip, mediolateral perturbation, and knee collapse. We found the following significant differences in the pre—near-falling gait cycle compared with the usual gait cycle: decreased gait velocity, prolonged total cycle time, and excessive mediolateral center of mass displacement.
Conclusions: Decreased gait velocity, prolonged cycle time, and excessive mediolateral center of mass displacement may be a sign of an impending fall in people with impaired gait after stroke.
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Falling is caused mainly by the inability to keep the center of mass (COM) projection within the base of support created by the feet as a result of external or internal perturbations. Normally, such postural instabilities are corrected by balance reactions.[1] However, individuals with stroke may have difficulty responding sufficiently to maintain postural balance because of impaired physical and/or cognitive functioning. Eighty percent of individuals with stroke have a balance disability,[2] and their fall rate is higher than that of age-matched healthy individuals.[3] Indeed, 55% of individuals with stroke have experienced 1 or more falls in the hospital.[4] Even after discharge, 4% sustain fractures because of a fall within 2 years, a rate 1.4 times greater than in the general population.[5]

To prevent falls, it is necessary to analyze how and why falls occur. Clinical observation tools are widely used in hospitals,[6] and falls have been analyzed based on hospital accident reports.[7] However, because falls occur unpredictably, little objective evidence is available on balance reaction impairments and causes of falls in individuals poststroke.

Various studies have attempted to kinematically analyze actual falling movements induced by external perturbations.[8-11] However, such falls are different from the actual falls that occur in hospitals. One study concluded that analysis of the response to forced gait perturbations did not help to predict falls.[12] A previous study analyzed actual falls recorded with 216 digital video cameras installed at various locations in long-term care facilities.[13] Although that study did not specifically analyze patients with hemiplegia, its methods facilitated the analysis of falling movements in a novel way. However, movement kinetics and kinematics were not analyzed in detail because of the 2-dimensional nature of the video data. Individuals with hemiplegia after stroke fall often, even on straight, flat walkways without any external disturbance.[14] Therefore, we decided to focus on how abnormal movements emerge from stable walking in the absence of external perturbations. Self-induced falls occur because of internal risk factors such as deficits in physical functioning (eg, reduced stability during stance phase).[3] Although it is difficult to record these falling movements kinematically and kinetically, detailed analysis of self-induced falls is necessary because in-hospital falls are a significant predictor of falls when individuals with stroke return home.[15]

The concept of near falls has recently been introduced and is attracting attention[16-18] because older adults often do not recognize the significance of near-fall events, which can lead to actual falls. A history of near falls in hospital is a strong predictor for an actual fall in individuals with stroke.[4] It may be possible to prevent accidental falls by analyzing the reason for near falls and the process leading up to them. However, only a few studies have investigated near-falls, for example, to develop sensors that detect near falls[16-18] or to count the number of near falls.[7,19]

However, in those studies, the process leading up to near-falls and the details of near-fall movements were not analyzed. One reason for the scarcity of previous studies on near falls is that such studies are difficult from an ethical viewpoint because inducing artificial falls or allowing falls to occur may harm participants. A potentially useful alternative would be to retrospectively analyze data on rarely measured near falls from databases. We are fortunate to have a database involving more than 1000 participants involved in more than 28,000 three-dimensional (3D) gait motion analysis sessions available for our use.

The purpose of this study was to test the hypothesis that several abnormal movements commonly occur immediately before near falls in individuals after stroke.

Methods

Routine gait measurement

We regularly monitor the gait of all patients in rehabilitation after stroke who can walk to objectively analyze the improvement in their gait. The gait of each patient is measured once a month, and gait data of about 200 patients are measured annually. These regular measurements were performed using a 3D motion capture system and 2 video cameras. A therapist always accompanies the patient to prevent falls during gait measurement.

Patients wore compressive athletic shorts and their own shoes and were allowed to use their own assistive device during gait trials, such as a cane and/or ankle-foot orthosis, under supervision. In each trial, the participant was instructed to walk on an 8-m walkway at a self-selected speed. At least 3 gait cycles were recorded for usual gait trials. Data collection was performed using a 3D motion capture system comprising 8 cameras,[a] 6 force plates (600mm × 400mm),[b] and 2 digital video cameras.[c]

Based on previous studies,[20-22] a total of 34 reflective markers were attached to define a 12-segment model including the thorax, pelvis, upper arms, forearms, thighs, shanks, and feet. Marker trajectories and force plate data were synchronized and measured at a sampling frequency of 100 Hz and were low-pass-filtered using a second-order Butterworth filter with cutoffs of 6 Hz and 18 Hz, respectively.[23] The COM position, gait velocity, trunk angle, and joint moments were calculated using an inverse dynamic model according to the Vicon Plug-In-Gait model. Kinetic and kinematic data were exported using a biomechanics analysis program (Visual 3D).[d]

Selection of participants

We selected near-falling trials by reviewing gait data of patients whose gait was routinely measured using a 3D motion capture system over 6 years between March 2012 and January 2018. All these participants were undergoing prolonged in-hospital rehabilitation, and none were community dwellers as would be the case in other countries such as the United States. Inclusion criteria were as follows: hospitalized in a convalescent rehabilitation ward, aged 20-90 years, and first unilateral stroke. We defined a "near fall" as a therapist feeling the need to stabilize a patient for a sudden gait instability during a 3D motion analysis assessment, according to previous study.[24] In this study, we added the following definition of a near fall, which combines subjective and objective components: "complete gait stop" accompanied by manual assistance from a therapist. Assistance to prevent a fall was assessed subjectively based on analysis of video data. Complete gait stop was assessed

objectively based on COM forward velocity of ≤0 m/s. The reasons for the near fall were visually classified according to previous studies.[16,25] No eligibility criteria were specified for type of stroke (ischemic or hemorrhagic), sex, or level of paretic limb motor dysfunction.

This study was approved by our university ethical committee (H30-29) and the hospital ethical committee (NRC3KR_2017_011). Written informed consent was obtained from all participants to record their gait using a 3D motion analysis system as part of their medical care, with the possibility that the data would be used for research. The nature of the research was explained on the hospital's website, and measures were taken to accept questions from prospective participants. Participants were informed that they could withdraw their participation at any time.

Measures

We analyzed differences in kinetic and kinematic parameters between the averaged usual gait cycle and pre−near-falling gait cycle (fig 1) for each patient. The usual gait cycle was averaged from 3 gait cycles in a usual gait trial. The pre−near-falling gait cycle was the last cycle before the near-falling gait cycle in a near-falling trial. We obtained the following gait parameters, in line with previous studies[26,27]: (1) gait velocity; (2) gait cycle duration; (3) mediolateral COM displacement; (4) step length; (5) step width; (6) joint moments; and (7) angular displacement of the trunk in a cycle. The peak values of joint moments and the trunk angular displacement in each gait cycle were calculated. Joint moments were calculated in the frontal plane for the hip joint and in the sagittal plane for the hip, knee, and ankle joints. Joint moments were calculated for the paretic limb. Step length and step width were the anteroposterior and mediolateral distances, respectively, between the heel markers at 2 consecutive initial contacts. Mediolateral COM displacement was calculated as the length between the maximum movement of the right and the left limbs in a gait cycle. Trunk angular displacement in a gait cycle was calculated as the angle between the peak-to-peak movement of flexion/extension, lateral flexion, and rotation. Step length and step width were normalized by body height, and joint moments were normalized by body weight.

Statistical approach

The pre−near-falling gait cycle and the corresponding averaged usual gait cycle were compared for each patient. The Shapiro-Wilk test was used to determine the normality of all parameters. Differences in parametric kinetic and kinematic data (such as spatiotemporal data, COM displacement, step length, step width, joint moments, and trunk angular displacement) were compared between the pre−near-falling gait cycle and usual gait cycle using the paired t test or the Wilcoxon signed-rank test. The level of significance was set at $P<.05$, and the effect size r was calculated for each index.[28] According to Cohen,[29] r values of at least 0.50, 0.30, and 0.10 indicate large, medium, and small effect sizes, respectively. Data were analyzed using SPSS Statistics version 24 for Windows.[e]

Results

A flowchart of participants in the study is shown in figure 2. By reviewing all video-recorded gait data of 28,519 trials (1056 patients) over 6 years, we identified 44 trials with near falls (33 patients). Based on the inclusion criteria, 36 gait trials (29 patients) were selected. Near falls had a number of specific characteristics, such as toe trip and
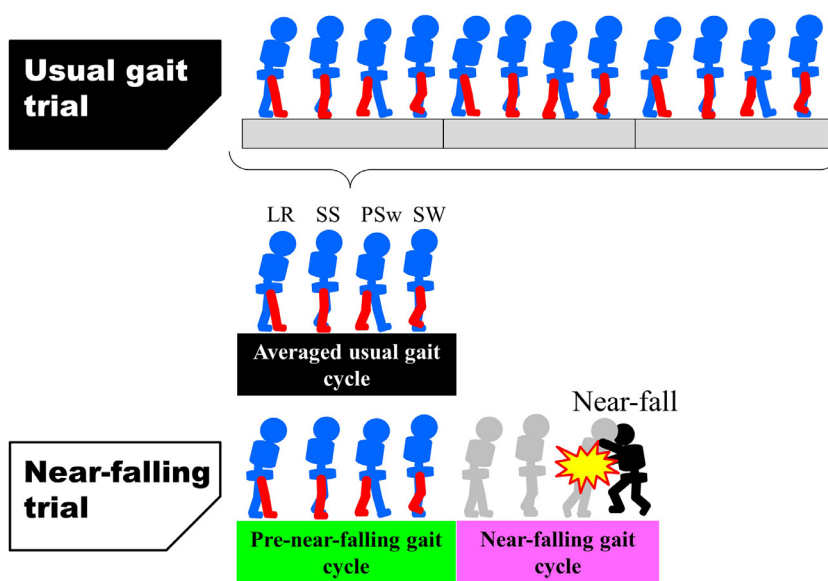
Fig 1   Two types of gait cycles were compared in this study: the averaged usual gait cycle in a usual gait trial and the pre−near-falling gait cycle (the last cycle before a near-falling gait cycle in a near-falling trial). The usual gait cycle and pre−near-falling gait cycle were compared in terms of differences in kinetic and kinematic parameters. Abbreviations: LR, loading response on the paretic side; PSw, preswing phase on the paretic side; SS, single-stance phase on the paretic side; SW, swing phase from initial swing to terminal swing on the paretic side.

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│ 28,519 gait trials measured using a 3D motion capture   │
│ system (1,056 patients)                                  │
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┌───────────────────────────────┐
│ • 28,477 successfully completed│◄──────┐
│   gait trials without manual   │   ┌────────────┐
│   assistance (1,023 patients)  │   │ Near-fall  │
└───────────────────────────────┘   └────────────┘
                            │
┌───────────────────────────────┐
│ • 2 gait trials with spinal cord│◄─────┐
│   injury (2 patients)          │   ┌────────────┐
│ • 4 gait trials with bilateral │   │ Inclusion  │
│   stroke (2 patients)          │   │ criteria   │
└───────────────────────────────┘   └────────────┘
                            │
┌───────────────────────────────┐  ┌──────────────────────┐
│ • 4 gait trials (4 patients)  │◄─│ 36 near-falling gait │
│   that immediately fell before │  │ trials (29 patients) │
│   the pre-near-falling gait    │  └──────────────────────┘
│   cycle was measured           │  ┌──────────────────────┐
└───────────────────────────────┘  │ Recorded pre-near-   │
                                    │ falling-gait cycle   │
                                    └──────────────────────┘
                            │
              ┌──────────────────────────────┐
              │ 32 pre-near-falling gait     │──► Analyzed in this study
              │ cycles (25 patients)         │
              └──────────────────────────────┘
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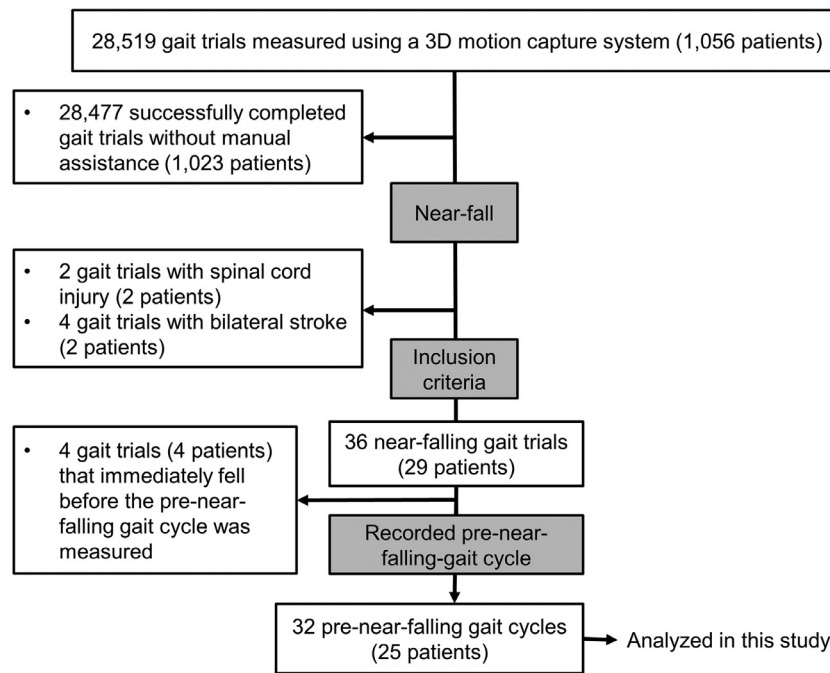
Fig 2 Flowchart of participants in the study.

mediolateral or backward perturbation. In the analysis of differences in kinetic and kinematic parameters between the usual gait cycle and pre−near-falling gait cycle, 4 gait trials were excluded because they nearly fell before the pre−near-falling gait cycle was measured. Therefore, 32 pre−near-falling gait cycle trials (25 patients) were finally extracted for analysis of abnormal kinetic and kinematic movement (table 1). Fourteen of the 25 participants used a cane. The reasons for a near fall in the 32 near-fall trials were toe trip (16 trials), mediolateral perturbation (5 trials), backward perturbation (10 trials), and knee collapse (1 trial). The visual signs that appeared 1 cycle before the near fall included slight toe trip, high steppage, and buckling knee. A slight toe trip in the pre-near-falling gait cycle tended to lead to actual toe trip in the near-falling gait cycle, high steppage tended to lead to backward perturbation, and buckling knee tended to lead to various near falls.

Kinetic and kinematic parameters in the pre−near-falling gait cycle of the 32 near falls were compared with the averaged values of the corresponding usual gait cycles. Differences in kinetic and kinematic parameters between usual and pre−near-falling gait cycles are shown in table 2. The COM forward velocity was significantly lower and the total cycle time was significantly longer in the pre−near-falling gait cycle. The movement duration tended to be prolonged, especially in the preswing phase. Mediolateral COM displacement was significantly larger in the pre−near-falling gait cycle than in the usual gait cycle, and the maximum hip abduction moment tended to be larger in the pre−near-falling gait cycle.

Discussion

We collected data on near-falling trials during gait in individuals poststroke to analyze the abnormal movements that occurred immediately before near falls in terms of kinematics and kinetics. We hypothesized that there would be several abnormal movements that commonly occur immediately before near falls in individuals after stroke. A number of abnormal movements were observed, including a decrease in walking speed and excessive lateral movement of the COM in the last cycle before the near-falling gait cycle. These results support our hypothesis that several movements would be a sign of an impending near fall immediately before the near-falling gait cycle. Individuals with hemiplegia after stroke experience complex falls in daily

Table 1 Patient characteristics

Characteristics	N=25
Age (y), mean ± SD	66.3±8.7
Time since stroke (d), mean ± SD	120.4±40.8
Sex (n), female/male	3/22
Paretic side (n), left/right	16/9
Type of stroke (n), hemorrhagic/ischemic	14/11
Height (m), mean ± SD	1.650±0.062
Weight (kg), mean ± SD	59.1±9.6
Trunk control test, (score out of 100), mean ± SD	64.0±34.8
BRS Lower extremity score (n), score out of 6	II: 2, III: 14, IV: 7, V: 2, VI: 0
FMA Lower extremity subscore, median (IQR) score out of 34	20.5 (7.0)
FMA Balance score, median (IQR) score out of 14	6.0 (5.0)
FMA Total sensory score, median (IQR score out of 24)	21.0 (11.5)

Abbreviations: BRS, Brunnstrom recovery stage; FMA, Fugl-Meyer Assessment; IQR, interquartile range.

Table 2 Differences in gait parameters between averaged usual gait cycle and pre−near-falling gait cycle (32 trials)

Variables	Usual Gait Cycle	Pre−near-falling Gait Cycle	P Value	Effect Size (r)
Spatiotemporal				
Gait velocity (m/s), median (IQR)	0.226 (0.116)	0.174 (0.148)	.010*	−0.480
Cycle time (s), median (IQR)	2.008 (0.636)	2.287 (1.504)	.017*	0.423
Loading response time (s), median (IQR)	0.408 (0.504)	0.346 (0.312)	.232	−0.211
Single stance time (s), median (IQR)	0.351 (0.275)	0.399 (0.302)	.217	0.218
Preswing time (s), median (IQR)	0.594 (0.691)	0.625 (0.826)	.078	0.312
Swing time (s), median (IQR)	0.644 (0.259)	0.582 (0.251)	.214	−0.220
COM movement				
Mediolateral displacement (m), mean ± SD	0.084±0.017	0.095±0.031	.021*	0.410
Step length				
Paretic side to nonparetic side (m/BH), mean ± SD	0.125±0.092	0.133±0.102	.633	0.090
Non-paretic side to paretic side (m/BH), mean ± SD	0.141±0.097	0.130±0.091	.320	0.180
Step width				
Paretic side to nonparetic side (m/BH), median (IQR)	0.074 (0.045)	0.076 (0.040)	.477	−0.126
Nonparetic side to paretic side (m/BH), median (IQR)	0.074 (0.042)	0.080 (0.033)	.837	−0.036
Joint moment				
Min plantar flexion in LR (Nm/BW), median (IQR)	0.014 (0.045)	0.015 (0.075)	.061	0.331
Max plantar flexion in stance (Nm/BW), mean ± SD	0.634±0.238	0.652±0.288	.530	0.110
Max knee extension in LR (Nm/BW), median (IQR)	0.090 (0.180)	0.128 (0.177)	.784	−0.049
Max knee flexion in stance (Nm/BW), mean ± SD	−0.231±0.289	−0.239±0.384	.811	0.040
Max hip extension in LR (Nm/BW), median (IQR)	0.312 (0.392)	0.280 (0.250)	.572	−0.103
Max hip abduction in stance (Nm/BW), mean ± SD	0.512±0.238	0.558±0.244	.079	0.320
Amplitude of trunk angle in a cycle				
Flexion-extension (deg), mean ± SD	8.752±3.203	10.016±5.183	.134	0.270
Lateral inclination (deg), median (IQR)	6.100 (3.387)	7.702 (7.355)	.550	0.106
Rotation (deg), mean ± SD	12.395±4.621	14.359±7.138	.103	0.290

NOTE. Internal joint moment: positive numbers=extensor/plantar, flexor/abductor.
Abbreviations: BH, body height (m); BW, body weight (kg); IQR, interquartile range; LR, loading response.
* $P<.05$.

life.[30] However, the functional problems that lead to actual falls as a result of complex movements are difficult to analyze. In this study, we collected near-falling trials during the simple task of walking 8 m, so it was possible to lessen biases arising from task complexity.

In our study, the process leading up to a near fall included slight toe trip, high steppage, and buckling knee. Although subjective, these observations from visual analyses are also valuable because few studies have detailed the process leading up to falls in patients with hemiplegia. Lee et al[16] classified causes of near falls into slip, trip, hit/bump, and misstep, but in our study the only signs of a near fall were trip and misstep under their classification because our study was centered on self-induced falls. Further retrospective analysis of a near-falling gait cycle is necessary to determine the etiology for near falls.

Although there were various near-falling patterns, several abnormal movements commonly occurred in the pre−near-falling gait cycle, such as increased mediolateral COM displacement and decreased gait velocity. In a previous study that described abnormal movements that occur immediately before falls in individuals with stroke, the abnormal movements were classified into 3 types: type 1, where falls had a larger prefall acceleration because of a faster swing on the paretic side; type 2, where the paretic leg did not swing properly and caught on the floor; and type 3, where falls were preceded by unstable walking patterns that

appeared a few steps before falling.[25] We found the same signs as in type 2 and type 3, such as lower gait velocity and larger mediolateral COM displacement, although no trials showed the same sign as in type 1 described in the previous study. This may be because the participants in the previous study were able to walk independently, whereas most participants of our study had low walking ability and needed assistance. Thus, the participants in this study may have lacked the physical ability to take a quick step reaction.

The reason for the decreased gait velocity and increased mediolateral COM displacement in the pre−near-falling gait cycle could not be clarified. However, several hypotheses can be put forward that would be consistent with results of this study. In the pre−near-falling gait cycle, there were various visible signs, such as a slight toe trip or buckling knee. In particular, toe trip is a major problem for individuals with lower limb dysfunction after stroke.[31] Because the tendency to prolong preswing may be related to decreased gait velocity and prolonged total cycle time, more detailed analysis is required to clarify why gait velocity decreased. These abnormal movements may reduce gait velocity, which in turn would increase mediolateral COM displacement of the COM.[32,33] This mediolateral displacement may have caused the internal perturbation that led to the near fall. However, there were various other reasons for decreased gait velocity and increased mediolateral COM displacement, such as high steppage or unpredictable buckling knee, and we believe

that excessive mediolateral COM displacement was caused by poor control in the paretic lower limb from midstance to the preswing phase. Additionally, hip abduction moment tends to increase in the pre—near-falling gait cycle. If walking speed decreases, the lateral movement of the COM increases, that is, the hip joint moves more to the affected side laterally, meaning that the hip joint abduction moment in the paretic stance phase may have tended to increase. Because gluteus medius muscle dysfunction is strongly associated with gait disturbance in individuals with stroke,[34] such inadequate mediolateral control may cause near falls. We predicted that this abnormal lateral displacement would be one of the causes of near falls.

To our knowledge, this study is the first report of near falling in individuals with stroke from the viewpoint of kinematics and kinetics. Our findings of decreased gait velocity and increased mediolateral COM displacement in the pre—near-falling gait cycle may aid caregivers in preventing falls during gait with guarded assistance.

Study limitations

There are several limitations to this study. First, we could not specifically identify whether a near fall as defined in this study was predictive of an actual fall because no patients actually fell. Thus, there is the risk of inaccuracy in assessing the presence and timing of near falls. However, we tried to identify near falls as accurately as possible using a definition with both subjective and objective components. Second, we could not specifically identify the physical and cognitive dysfunction in patients who nearly fell because this study analyzed only the kinematic movement before the near fall. Third, because most of the participants were men, the extracted data have sex bias. Lastly, although there were multiple directions and timings of near falls, we could not analyze each pattern. Additionally, 14 participants used a cane on the nonaffected side and the joint moments of the nonparetic limb could not be measured. Nevertheless, because we were able to clarify abnormal movements that occur in the last cycle before the near-falling gait cycle, we believe that our findings can contribute to fall-prevention strategies and the development of rehabilitation programs for individuals poststroke.

Conclusions

This study provides interesting kinetic and kinematic data for understanding what occurs during the last gait cycle before a near fall in individuals with stroke. However, there are various reasons for near falls, with abnormal movements commonly observed in the last cycle before the near-falling gait cycle, including decreased gait velocity, prolonged total cycle time, and excessive mediolateral movement of the COM. This is useful knowledge for providing walking assistance and for preventing falls after stroke.

Suppliers

a. Eight-camera motion capture system; Vicon Nexus, Oxford Metrics.
b. Six force plates; Advanced Mechanical Technology Inc.
c. Two digital video cameras; Sony.
d. Visual 3D software version 6; C-Motion Inc.
e. SPSS Statistics version 24 for Windows; IBM.

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