

Gait Deviation Associated with Absent Terminal Stance Phase in People with Stroke

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Purpose The purpose of this study was to identify gait deviations during the four rocker phases of gait cycle in people with stroke compared to healthy adults. **Methods** Fourteen community-dwelling stroke subjects (9 males, 5 females) with unilateral hemiparesis and fifteen healthy adults (10 females, 5 males) had video recording as they walked a five-meter walkway to analyze the four phases of the gait cycle (loading response, midstance, terminal stance, and pre-swing). Subjects performed the five times sit to stand (5STS) test to measure the severity of strength and balance deficits. The distance and time for the four phases and the speed of steady state of walking were measured using a movement analysis software (Dartfish ProSuite 9). This study used the multivariate analysis of variance technique with one fixed factor (group) to identify the multivariate effect of distance, time, and speed related to four consecutive phases. **Results** The distance and time of the four consecutive phases of gait were significantly different in stroke subjects compared to healthy subjects ($p < 0.05$). Specifically, the fore-foot rocker, or terminal stance phase, was absent in all stroke subjects which increased their double limb support time resulting in slow gait speed compared to the healthy control group ($p < 0.05$). **Conclusions** People with stroke demonstrated reduced body forward progression over four rocker phases compared to the healthy control during a steady state of walking. The ratio of the four rocker phases can be used to specify the gait deviation for clinicians to improve post-stroke hemiplegic gait.

Key words Stroke, Gait, Four rocker phases, Terminal stance, Double limb support time

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1. Introduction

Stroke survivors with hemiplegia experience asymmetrical gait pattern that have limited their functional independence during daily living and threatens quality of life.¹⁾ Gait abnormality can be clinically observed on the paretic side depending on the severity of muscle weakness, spasticity or compensatory mechanisms.²⁾ Therefore, objective measurement of hemiplegic gait abnormalities is vital to develop a clinical gait training methodology to optimize walking performance in people with hemiparesis.⁴⁾

Clinically, gait deviations can be identified when the complex events of gait are broken down into distinct and smaller steps while observing a gait cycle. Gait cycle is the term that is used to describe the se-

quence of the rhythmic movements of the body leading to forward progression in the environment.⁵⁾ While the body is achieving forward progression during a steady state of walking, dynamic stability is necessary during the stance phase. Balance of the body is accomplished through a series of rockers in the ankle and foot of the stance leg while preparing to advance forward during ambulation.⁶⁾ Perry²⁾ divided the events of rockers into four phases: 1) heel rocker, 2) ankle rocker, 3) forefoot rocker, and 4) toe rocker. First, the heel rocker phase occurs during the loading response stage. It involves the heel to serve as a pivot point on the foot for the first body forward progression while walking. Secondly, the ankle rocker phase happens at the beginning of the midstance stage when the pivot transitions from the heel to the ankle. The proximal aspect of the leg shifts forward on the ankle as the limb advances. Thirdly, the fore-

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foot rocker phase begins as the leg transitions to terminal stance. This is when the heel comes off the ground and the pivot point shifts to the metatarsal heads and the forefoot. Forward progression is accelerated as the body weight is less supported by the foot. Lastly, the toe rocker phase occurs during the pre-swing stage. The final pivot point is transitioned to the toes as the body prepares for the swing phase. These four rocker phases are essential to maintain normal gait performance and to produce a smooth shift in the center of gravity (COG).^{6,7)}

During the four rocker phases, the COG can shift outside of the base of support challenging the person's dynamic balance. The COG can be restored by incorporating proper posture and muscle forces to maintain equilibrium. Challenges imposed to the COG during locomotion can affect the person's dynamic stability and energy conservation.⁸⁾ These alterations may cause individuals to walk in a narrow base of support and lose their balance. Kanzaki⁷⁾ challenged the biomechanical role of the fore-foot rocker phase using a sole plate to limit the metatarsophalangeal motion of a person's foot. This mimicked a joint contracture causing limited dorsiflexion on the metatarsal-phalangeal joint.

The four rocker phases of gait produce a smooth shift in the body's center of gravity as the body advances forward and are essential to maintain normal gait performance. A disturbance to a rocker phase imposes a challenge to the person's walking stability. There is limited research as to which of the four consecutive forward progression phases is most affected in people with stroke during walking. Traditional methods that have been used to analyze gait abnormalities include observational gait analysis through the naked eye and computerized, quantitative gait assessments. Observational gait analysis has been found to lead to poor validity and reliability.⁹⁾ However, quantitative measures of gait characteristics are a gold standard for gait assessment since these methods have been proven to have higher sensitivity compared to observational techniques.¹⁰⁾ In this study, a novel approach will be used to obtain valid quantitative information during gait analysis.

We hypothesize that people with stroke will demonstrate reduced body forward progression over four rocker phases compared to the healthy subjects during a steady state of walking, and the fore-foot rocker phase for stroke subjects will be a diminished period that will prolong the double limb support time during their steady gait.

II. Materials and Methods

This study was approved by The University of Texas Medical Branch at Galveston institutional review board. Informed consent was obtained from all the subjects before participating in this study.

1. Study subjects

(1) Healthy Participants

Fifteen healthy young and middle-aged adults (10 females, 5 males) with ages ranging from 28 to 38 years (33.20 ± 3.53) were considered for this study. Subjects were volunteers from the community and were excluded if they had a history of neurological or orthopedic conditions.

(2) Stroke Participants

Fourteen community-dwelling stroke subjects (9 males, 5 females) with unilateral hemiparesis volunteered to participate in this study. The ages ranged from 36 to 78 years (56.46 ± 12.22). Stroke duration ranged from 8 to 84 months (34.07 ± 23.95) from the date of onset. Stroke subjects were required to be capable of walking five meters at their comfortable speed with guarded assistance. Subjects were excluded if they were unable to follow verbal commands, demonstrated poor walking endurance, and had a history of neurological or orthopedic conditions in addition to the stroke. The characteristics of the stroke subjects are presented in (Table 1).

2. Procedure

(1) Gait assessment

Each subject from the healthy and stroke groups were instructed to walk individually along a marked

Table 1. Description of subjects with hemiparesis

Subject	Age, years	Gender	Diagnosis	Stroke duration, months	Assistive device	Body mass index	5STS test, seconds
1	45	M	R basal ganglia	38	Ambulator	32.3	19.41
2	71	F	R CVA	25	Wheelchair	36.9	18.59
3	60	F	R CVA infarct	29	Roller	21.6	12.8
4	56	F	R CVA	35	Cane	25.4	12.3
5	52	M	R CVA	22	Single tip cane	27.6	19.8
6	37	M	L CVA infarct	15	Quad cane	23.8	24.7
7	63	M	L MCA, hem	60	AFO	26.9	21
8	36	M	L infarct	23	Ambulator	32.1	13.24
9	54	F	L infarct	12	Rolling Walker	28.7	15.49
10	54	M	L infarct	42	Cane	25.8	27.27
11	46	M	R CVA	9	Ambulator	30.5	13.24
12	60	M	L hem	8	Cane	28.3	18.64
13	78	M	L infarct	75	Ambulator	29	16.33
14	67	F	L infarct	84	None	26.1	20.68
Mean	56.46			34.07		28.21	18.11
(SD)	12.22			23.95		3.89	4.53

Abbreviations: Gender: M = male; F = female; Diagnosis: L = left, R = right, CVA = cerebrovascular accident, MCA = middle cerebral artery, hem = hemorrhage; Assistive device: AFO = ankle foot orthosis; 5STS = 5-repetition sit-to-stand

five-meter walkway at their self-selected speed on an even surface indoors. Using markers, the five-meter walkway was divided into a one-meter zone for acceleration, a central three-meter zone for steady state of walking, and a one-meter zone for deceleration. Healthy subjects were instructed to incorporate a “heel-to-toe” walking pattern, upright posture, and natural arm swing to demonstrate healthy gait mechanics. Stroke subjects were instructed to walk without an assistive device. All stroke subjects wore a gait belt and were provided with contact guard assist by a research assistant during their walk. All healthy and stroke subjects wore flat shoes that allowed a proper visual of their walking pattern.

A video camera (Cannon XC10 4K Camcorder) was used to record each healthy and stroke subject. The video camera was placed on a tripod at a five-meter distance, perpendicular to the walkway, and was positioned to capture the movement of the whole body of

each subject during their walk. Healthy subjects were recorded from the right lateral view of their body only and the stroke subjects were recorded from the non-paretic and paretic lateral views separately. Healthy subjects walked a total of three trials. Stroke subjects walked a total of six trials (three trials on the non-paretic side and three trials on the paretic side).

All trials captured on video for each subject (healthy and post stroke) were analyzed with a movement analysis software, the Dartfish ProSuite 9. All video trials were examined using the software’s analyzer feature. In each video, the one-meter zone for acceleration, the three-meter zone for steady state of walking, and the one-meter zone for deceleration were labeled using the software’s distance measuring feature. The video image during steady state of walking was used to identify each phase of gait cycle and the acromion during steady state walking was tracked to measure the distance and time.

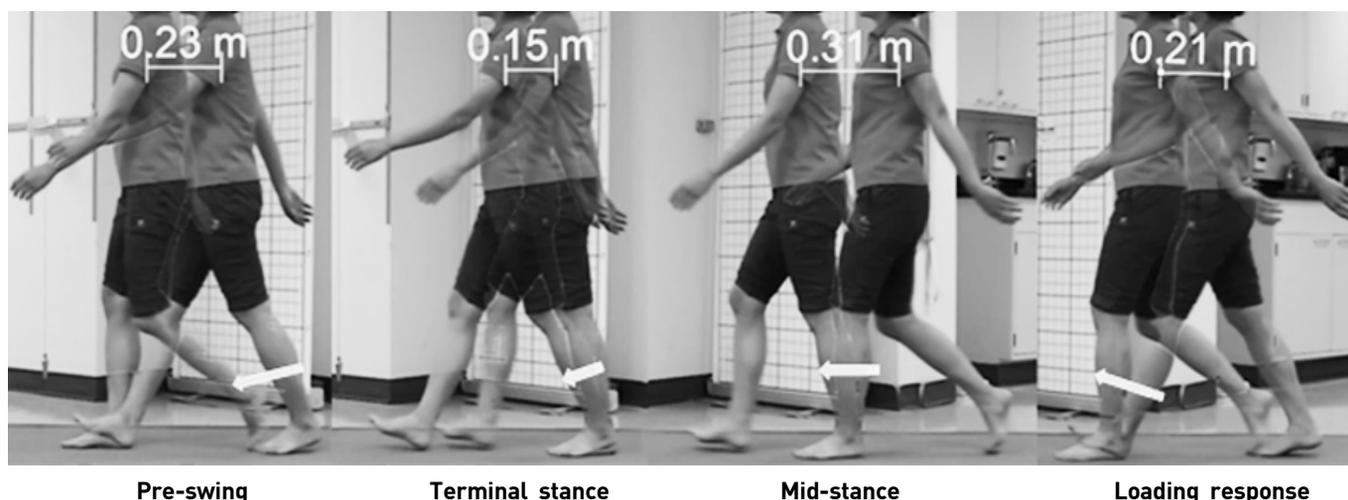


Figure 1. Four consecutive forward progression phases and body forward: Pre-swing (toe rocker), Terminal stance (fore-foot rocker), Mid-stance (ankle rocker), and Loading response (heel rocker).

(2) Data Collection

① 5-repetition sit-to-stand (5STS) test

Each subject from the healthy and stroke groups were asked to perform the 5STS test prior to the experiment. The 5STS test was performed to evaluate quadriceps strength and dynamic balance of each subject.^{11, 12)} Both groups were asked to stand from sitting five times as quickly as possible from a 16-inch-high chair with armrests. Stroke subjects were instructed to avoid using an assistive device. Gait belts were placed on the stroke subjects for safety purposes. Both groups were instructed to cross their arms across their chest, stand up completely from the chair, and make firm contact with the chair when sitting. Timing on a stopwatch began when each subject was commanded to begin the test by standing from the chair and ended when each subject sat down after the fifth repetition.

② Distance and time for the four phases of gait

The four phases of the gait cycle (loading response, midstance, terminal stance, and pre-swing) were analyzed on both lower extremities of each subject from both groups. The distance for each phase was measured in meters using the software's distance measuring feature. The time for completion of each phase was calculated in seconds using the software's video

time tracker. The subject's acromion process was used as a reference to measure the distance and time between each phase of the gait cycle (Figure 1). The loading response phase was measured when one lower extremity began at initial contact and ended when the opposite lower extremity performed toe-off. The midstance phase was measured when the opposite lower extremity performed toe off and ended when the other lower extremity performed heel rise. The terminal stance phase was measured when one lower extremity performed heel off and ended when the opposite lower extremity performed initial contact. Finally, the pre-swing phase was measured when the opposite lower extremity performed initial contact and ended when the other lower extremity performed toe-off.

③ Speed for steady state of walking

The speed for steady state of walking, in the three-meter zone of the walkway, was calculated in each trial for each subject from both groups. Once each subject began walking on the walkway, the timing for the steady state of walking commenced when the subject's acromion process reached the two-meter mark and ended when the subject's acromion process reached the four-meter mark. The three-meter distance and the length of time of the steady state of walking were

divided to determine the gait speed in meters/second.

④ Statistical design

Since all the initial measures of gait parameters met the normality and homogeneity, this study used the multivariate analysis of variance techniques with one fixed factor (group) to identify the multivariate effect of distance, time, and speed related to four consecutive phases (loading response, mid-stance, terminal stance, and pre-swing). A multivariate F value was obtained from Wilks lambda. To identify which phase of stance were significantly different from others during a steady state gait, we used post-hoc univariate F tests. The Bonferroni test was used for multiple comparisons with respect to three different groups (1. Paretic side, 2. Non-paretic side, and 3. Healthy control). The p-value of less than 0.05 was considered to determine the statistical difference. All data were analyzed using the IBM Statistical Package for the Social Sciences (SPSS 25 for Windows; SPSS Inc, Chicago, Illinois).

III. Results

1. Forward progression of the body in distance

The multivariate main effect (Wilks lambda) for forward progression of the body in distance was significant ($F_{8,74} = 9.18$, $P < 0.05$). The univariate main effect was significant for only terminal stance ($F_{2,40} = 50.07$, $P < 0.05$). Bonferroni tests showed that the terminal stance phase was significantly longer in healthy control (Mean = 0.1meter, SD= 0.05meter) than both the paretic and the non-paretic sides because the terminal stance phase was absent in people with stroke.

2. Forward progression of the body in time

The multivariate main effect (Wilks lambda) for forward progression of the body in time was significant ($F_{8,74} = 17.40$, $P < 0.05$). The univariate main effects were significant for loading response ($F_{2,40} = 4.39$, $P < 0.05$), mid-stance ($F_{2,40} = 24.20$, $P < 0.05$), terminal stance ($F_{2,40} = 62.99$, $P < 0.05$), pre-swing ($F_{2,40} = 6.29$, $P < 0.05$). Bonferroni tests showed that the loading response was significantly shorter in healthy control

(Mean = 0.22 second, SD= 0.02second) compared to both the paretic (Mean = 0.35 second, SD= 0.20 second) and the non-paretic sides (Mean = 0.38 second, SD= 0.19 second) in people with stroke. The mid-stance was significantly shorter in healthy control (Mean = 0.30 second, SD= 0.04second) compared to the non-paretic side (Mean = 0.45 second, SD= 0.06 second), but not different from the paretic side (Mean = 0.33 second, SD= 0.07 second) in people with stroke. The terminal stance phase turned out significantly longer in healthy control (Mean = 0.08 second, SD= 0.04second) due to the absence of terminal stance in people with stroke. The pre-swing was significantly shorter in healthy control (Mean = 0.20 second, SD= 0.03second) compared to the paretic side (Mean = 0.39 second, SD= 0.20 second), but not different from the non-paretic side (Mean = 0.32 second, SD= 0.14 second) in people with stroke.

3. Forward progression of the body in speed

The multivariate main effect (Wilks lambda) for forward progression of the body in speed was significant ($F_{8,74} = 48.33$, $P < 0.05$). The univariate main effects were significant for terminal stance ($F_{2,40} = 389.99$, $P < 0.05$) and pre-swing ($F_{2,40} = 6.47$, $P < 0.05$). Bonferroni tests showed that the terminal stance phase was significantly faster in healthy control (Mean = 1.21m/s, SD= 0.23m/s) than both the paretic and the non-paretic sides because of absence of terminal stance phase in people with stroke. The pre-swing was significantly faster in health control (Mean = 1.22 m/s, SD = 0.14 m/s) than both the paretic side (Mean = 0.76 m/s, SD = 0.47 m/s) and the non-paretic side (Mean = 0.83 m/s, SD = 0.44 m/s).

IV. Discussion

In this study, we found that the distance and time of the four consecutive phases of gait and the speed of steady state of walking were significantly different in stroke subjects compared to healthy subjects. Our findings demonstrated that the reduced distance of forward progression of the body for stroke subjects

was due to the absence of the terminal stance phase on both paretic side and non-paretic side. The healthy subjects covered a longer distance during the terminal stance phase (Mean = 0.1 meter) increasing their forward progression of the body compared to stroke subjects (Mean = 0 meter). Second, the time for forward progression of the body in stroke subjects was greater compared to healthy subjects due to the increased duration of the following phases: loading response (Mean = 0.35 seconds for paretic side, Mean = 0.38 seconds for non-paretic side, and Mean = 0.22 seconds for healthy), midstance (Mean = 0.45 seconds for non-paretic side and Mean = 0.30 seconds for healthy), and pre-swing (Mean = 0.39 seconds for paretic side and Mean = 0.20 seconds for healthy). Lastly, stroke subjects demonstrated reduced speed of forward progression of the body during steady state of walking due to absence of the terminal stance phase compared to healthy subjects (Mean = 1.21m/s), and the speed of paretic and non-paretic limb advancement during the pre-swing phase was less on stroke subjects (Mean = 0.76 m/s for paretic side and Mean = 0.83 m/s for non-paretic side) compared to healthy subjects (Mean = 1.22 m/s).

The stroke subjects in this study demonstrated an absence of the terminal stance phase during all gait cycles on the paretic side and non-paretic side leading to a disturbance in the distance and time of forward progression of the body. Mulroy, et al. found that during the stance phase (loading response, midstance and terminal stance) on the paretic side there is insufficient activation of the plantarflexors resulting in poor control of the tibia.¹³⁾ The stiffness of the ankle, produced by weakness of the plantarflexors, disrupts the forward advancement of the tibia during the midstance phase resulting in hyperextension of the knee or genu recurvatum.^{13, 14)} The knee hyperextension that occurs on the paretic limb assists in preventing the body to collapse during the midstance phase.¹⁵⁾ The genu recurvatum phenomenon causes the body's COG to shift upwards causing a disruption on walking stability.¹⁴⁾ As a result, symmetrical gait patterns in people with stroke become difficult to achieve. There is inadequate active weight shifting onto the

paretic limb during steady state of walking which leads to heavy loading on the non-paretic limb during its loading response, midstance and terminal stance phases.^{3, 16)} This increased body weight placed on the non-paretic limb interrupts heel rise to occur which affects the forward progression of the body. The increased time for forward progression of the body of stroke subjects may be due to compensatory mechanisms caused by muscle weakness. The hip and knee extensor muscles of the paretic limb synergistically activate during the loading response, midstance and terminal stance phases.¹⁾ This abnormal activation does not assist the weak anterior tibialis muscle to perform ankle dorsiflexion for foot clearance. To compensate for these impairments, people with stroke perform hip hiking and circumduction of the paretic limb to advance to the pre-swing phase.¹⁷⁾ Additionally, people with stroke demonstrate lateral trunk motion during walking that can be caused by weak hip abductor muscles. Weakness of the hip abductor muscle called gluteus medius causes an apparent pelvic drop during the single stance of the paretic limb. The pelvic drop indicates a positive Trendelenburg sign. People with stroke compensate for this pelvic drop by performing lateral trunk flexion to the paretic side.¹⁸⁾

This study demonstrated that stroke subjects have a decreased walking speed during the four consecutive phases of gait compared to healthy subjects. According to Hsu, Tang, and Jan, gait performance in people with stroke is characterized with slow velocity and left-right asymmetry compared to healthy adults.¹⁹⁾ The asymmetry observed in the gait of people with stroke can be characterized by spatial and temporal differences between the paretic and non-paretic limbs. Patterson et al. found that spatial asymmetries occur during step length and temporal asymmetries occur during the stance time (mid-stance and terminal stance phases), swing time (pre-swing phase), single limb stance time and double limb support time in the gait of people with stroke.²⁰⁾ These spatiotemporal parameters and altered muscle activation of the lower limbs have an impact on the smoothness of forward progression of the body during stroke gait performance. The stroke subjects in our study demon-

strated decreased speed of forward body progression during their gait possibly due to increased duration of double limb support and single limb stance on the non-paretic side. The period of double limb support increases (3.11 seconds) when the paretic side accepts body weight during the midstance and terminal stance phases combined which augments the time required to complete forward body progression.^{21, 22)} During single limb stance on the non-paretic side, the total body weight is accepted while the paretic limb is advanced during the pre-swing phase. An increase in time of single limb stance on the non-paretic limb (0.53 seconds) may indicate difficulty of advancing the paretic limb and require additional time to execute toe clearance.¹⁹⁾ In addition, an increase in time of single limb stance on the paretic limb (0.42 seconds) may occur due to hyperextension of the knee and increased muscle tone in the plantarflexor muscles.^{19, 21)} By identifying the mechanisms underlying abnormally long time spent during double limb support and single limb stance, appropriate treatment strategies can be implemented to increase the walking speed of people with stroke.

The community-dwelling stroke subjects in our study demonstrated a mean self-selected walking speed of .61 m/s during steady state of walking compared to the healthy control with a mean self-selected walking speed of 1.18 m/s. According to Braden, individuals with a walking velocity of 0.4 to 0.6 m/s are considered community ambulators with an unhindered path but may have difficulty in crowded areas.²³⁾ Studies identified normative data of age-based self-selected walking speed for healthy community dwelling men and women that can be used to compare with the walking velocities of people with stroke.^{23, 24)} We found the gait speed for our male stroke subjects, with ages ranging from 30-79 years, was slower at 0.31-1.04 m/s compared to the healthy age-based walking speed for male subjects at 1.43-1.26 m/s.^{23, 24)} For our female stroke subjects with ages ranging from 54-71 years, we found their gait speed was slower at 0.30-0.68 m/s compared to the healthy age-based walking speed for female subjects at 1.31-1.13 m/s.^{23, 24)} Variables such as impaired muscle strength, bal-

ance, and lower extremity motor function can possibly be affecting community-dwelling people with stroke preventing them to walk at a faster speed.²⁵⁾ Walking deficits and impaired dynamic balance causes an increase in the energy cost of walking and risk for falls. A study demonstrated that people with stroke walking at faster speeds of 1.0 m/s decreases the energy cost of walking.²⁶⁾ Therefore, it is important for clinicians to target balance impairments and assist with increasing the walking speed during post-stroke rehabilitation programs.

In our study, the stroke and healthy subjects performed a timed 5STS test to compare possible impairments in lower limb muscle strength and dynamic balance.^{12, 27, 28)} Our findings demonstrated that stroke subjects performed a 5STS test at an increased time (Mean = 18.11 second, SD = 4.53 second) compared to healthy subjects (Mean = 7.84 second, SD = 1.20 second). It is possible that people with stroke demonstrate longer duration (17.1 seconds) when completing the 5STS test compared to healthy young adults (8.9 seconds) due to muscle weakness of the lower limbs and adoption of compensatory strategies that lead to instability.^{27, 29)} Compensatory strategies that have been demonstrated during a 5STS test include lateral trunk deviation towards the non-paretic side and lack of full knee extension on the paretic limb causing asymmetric weight bearing during a sit to stand transition.²⁹⁾ The 5STS test has been employed to determine the isometric strength of the knee extensor (quadriceps femoris) muscles as it assists to accelerate and decelerate the body's mass against gravity when performing this test.³⁰⁾ Studies have shown that decreased knee extensor muscle strength is associated with poor balance control that can lead to falls in the stroke population.^{31, 32)} Research from Guralnik et al. demonstrated that people with stroke who completed a 5STS in more than 16.7 seconds are more likely to have a disability in the activities of daily living and functional mobility.³³⁾ In addition, researchers found that the 5STS test is correlated with gait speed after scores of 13 seconds or more on the 5STS test was a clinical determinant of poor performance of the 6-minute walk test.³⁴⁾ Clinicians can use the 5STS test as an

outcome measure that can be correlated with gait speed and determine the level of disability of people with stroke.

This study identified that people with stroke demonstrated reduced body forward progression over four rocker phases compared to the healthy subjects during a steady state of walking. Our results demonstrated that the fore-foot rocker, or terminal stance phase, was absent in all stroke subjects which increased their double limb support time resulting in slow gait speed.

Quantitative measures of gait characteristics are a gold standard for gait assessment since these methods have been proven to have higher sensitivity compared to observational techniques. The ratio of the four rocker phases can be used to quantify the severity of the gait abnormalities in stroke survivors. By identifying the factors that contribute to these deviations, clinicians can target interventions to the fundamental gait characteristics and improve the walking efficiency of these individuals.

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