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Gait differences between individuals with post-stroke hemiparesis and non-disabled controls at matched speeds

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Abstract

Treadmill walking was used to assess the consistent gait differences between six individuals with post-stroke hemiparesis and six non-disabled, healthy controls at matched speeds. The hemiparetic subjects walked on the treadmill at their comfortable speeds, while each control walked at the same speed as the hemiparetic subject with whom he or she was matched. Kinematic and insole pressure data were collected from multiple, steady-state gait cycles. A large set of gait differences found between hemiparetic and non-disabled subjects was consistent with impaired swing initiation in the paretic limb (i.e., inadequate propulsion of the leg during pre-swing, increased percentage swing time, and reduced knee flexion at toe-off and mid-swing in the paretic limb) and related compensatory strategies (i.e., pelvic hiking and swing-phase propulsion and circumduction of the paretic limb). Exaggerated positive work associated with raising the trunk during pre-swing and swing of the paretic limb, consistent with pelvic hiking, contributed to increased mechanical energetic cost during walking. A second set of gait differences found was consistent with impaired single limb support on the paretic limb (i.e., shortened support time on the paretic limb) and related compensatory strategies (i.e., exaggerated propulsion of the non-paretic limb during pre-swing to shorten its swing time). Other significant gait differences included asymmetry in step length and increased step width. We conclude that consistent gait differences exist between hemiparetic and non-disabled subjects walking at matched speeds. The differences provide insights, concerning hemiparetic impairment and related compensatory strategies, that are in addition to the observation of slow walking speed.
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Keywords: Gait; Stroke; Biomechanics; Speed; Symmetry

1. Introduction

Gait in individuals with post-stroke hemiparesis is characterized by reduced speed, cadence, stride length, and joint angular excursions [1,2]; asymmetry in temporal, spatial, kinematic, and kinetic gait variables [3-6]; and increased mechanical energetic cost [7,8]. The improvement of these gait deviations has been stressed in gait rehabilitation, since it may improve locomotor performance in hemiparetic individuals. However, many of these deviations may be consistent with slower walking in non-disabled individuals and simply restate the observation that hemiparetic individuals walk slower than normal. The gait differences between hemiparetic and non-disabled individuals while walking at the same speeds may provide insights, concerning hemiparetic impairment and related compensatory strategies, that are in addition to the observation of slow walking speed.

In this pilot study, we compared the gait of individuals with post-stroke hemiparesis and non-disabled controls while they walked on a treadmill at matched speeds. Treadmill walking facilitated the matching of speed between hemiparetic and non-disabled subjects and the comparison of kinematic and insole pressure data from multiple, steady-state gait cycles. We hypothesized that consistent gait differences would exist between the hemiparetic and non-disabled subjects at matched speeds.

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2. Methods

2.1. Subjects

Six individuals with a single cerebrovascular accident and resultant hemiparesis were selected from the VA Palo Alto Health Care System outpatient population. Inclusion criteria for this study were (1) a single stroke at least 6 months prior to study, (2) ability to walk independently overground with use of an ankle foot orthosis (AFO) or assistive device, and (3) ability to advance the paretic limb independently while walking on a treadmill. Each subject's lower extremity functional motor level was quantified using the Fugl-Meyer Assessment of motor function [9]. Six non-disabled individuals were recruited to serve as gender, age (within ± 10 years), height (within ± 6 cm), and weight (within ± 12 kg) matched controls for the hemiparetic subjects. The non-disabled controls exhibited normal joint range of motion and muscle strength and had no apparent gait abnormalities. Subject characteristics are presented in Table 1, ordered by the hemiparetic subjects' comfortable walking speeds on the treadmill. All procedures were approved by the Stanford University administrative panels on human subjects and were consistent with the Declaration of Helsinki.

2.2. Instrumentation

Subjects wore a Medical Harness (Robertson Mountaineering, Henderson, NV) attached to an overhead support as they walked on a Rehabilitation Treadmill (Biodex Medical Systems, Shirley, NY). During treadmill walking, the harness did not provide body weight support but served as a safety catch if subjects were to fall. Pedar insole pressure sensors (Novel, Munich, Germany) were placed inside the subjects' shoes to determine foot contact. For subjects who wore an AFO, the sensors were placed inside the AFO.

Bilateral kinematics were captured at 50 Hz using a Qualisys Motion Analysis System (Qualisys Inc., East Windsor, CT), incorporating five digital ProReflex cameras. Eight clusters of three reflective markers were located on the upper trunk and pelvis and right and left thighs, shanks, and feet and calibrated to anatomical reference points to define each segment's position and orientation. A voltage signal coinciding with each camera exposure initialization was used to synchronize the insole pressure readings.

2.3. Protocol

The hemiparetic subjects walked on the treadmill at their comfortable speeds (range: 13–45 cm/s; Table 1) as determined during single pre-sessions where the subjects were familiarized to treadmill walking. Each non-disabled control walked at the same speed as the hemiparetic subject with whom he or she was matched. Hemiparetic subjects who normally wore an AFO walked with the AFO on the treadmill. All subjects were asked to hold onto the handrails as the treadmill belt accelerated and release hand hold once the prescribed speed was reached. After subjects achieved steady state without handrail hold, data was collected for 20 s. Two subjects failed to walk for 20 s without handrail hold, but data for at least five complete gait cycles were collected from these individuals.

2.4. Data reduction and analysis

The raw kinematic data were post-processed in MARey (Center for Locomotion Studies, Penn State University, State College, PA) to obtain knee flexion and ankle dorsiflexion angles; joint center trajectories of the hip, knee, and ankle; and anatomical trajectories of the acromion processes and tip of the second toe and heel of each foot. The joint center and anatomical trajectories were fitted to a seven-segment inertial model of each subject, consisting of a trunk (including the mass of the head and arms), two thighs, two shanks, and two feet (including the mass of the shoes), based on data collected by Dempster et al. [10]. Hip flexion/extension angle was defined to be the angle between the axes of the femur and trunk in the sagittal plane, which was defined by the mid-line between the hip joint centers and

Table 1
Hemiparetic (H1–H6) and non-disabled (N1–N6) subject characteristics

	Subject no.						
	H1/N1	H2/N2	H3/N3	H4/N4	H5/N5	H6/N6	Mean (S.D.)
Gender	M/M	M/M	F/F	M/M	F/F	F/F	
Age (years)	52/60	66/60	64/67	68/72	56/58	56/49	60 (7)/61 (8)
Height (cm)	170/176	175/172	161/161	158/159	167/161	169/163	167 (6)/165 (7)
Weight (kg)	84/94	77/66	66/55	66/66	54/54	54/52	67 (12)/64 (12)
SSWS (cm/s)	22/111	33/138	59/149	72/113	56/146	77/147	53 (22)/134 (17)
CTS (cm/s)	13/13	31/31	36/36	36/36	45/45	45/45	34 (12)/34 (12)
Time post-stroke (months)	28	20	45	122	8	40	44 (41)
Affected side	R	R	L	L	R	L	
LE Fugl-Meyer (max = 34)	16	20	16	24	27	22	21 (4)
Assistive device (s)	AFO cane	Cane	AFO cane	AFO	Cane		

Individual characteristics and group means and standard deviations (S.D.). Abbreviations: LE, lower extremity; AFO, ankle-foot orthosis; SSWS, self-selected overground walking speed; CTS, comfortable treadmill speed.

acromion processes. A measure of limb circumduction during swing was defined as the peak lateral displacement of the foot center of mass during swing relative to its lateral position during stance.

The post-processed kinematic data were interpolated from 50 to 100 Hz; filtered using a second-order Butterworth, low-pass filter (fc = 6 Hz); and differentiated to obtain segment linear and angular velocities. The kinetic (KE), potential (PEG), and mechanical (ME = KE + PEG) energies of the segments were then obtained from the segments' positions and velocities [11]. Kinetic, potential, and mechanical energetic cost was defined as the summed positive increments in these energies during a gait interval or stride [12] (Fig. 1). For visual inspection, the kinematic and energetic gait trajectories were normalized to percent gait cycle, beginning and ending with initial contact of each foot, and ensemble averaged over the gait cycles collected.

The periods of stance and swing of each limb were determined using a threshold on the vertical ground reaction force ($F > 35$ N), as estimated by the insole pressure data (interpolated from 50 to 100 Hz). Step length was defined as the forward distance between initial contact of one foot and the previous initial contact of the other foot.

Asymmetries in swing time and step length were quantified using a modified version of an index (Eq. (1)) proposed by Robinson et al. [13]:

$$\text{Asymmetry}\,(\%) = \frac{100(V_{\text{paretic}} - V_{\text{non-paretic}})}{\max(V_{\text{paretic}}, V_{\text{non-paretic}})} \qquad (1)$$

where V_{paretic} is the value of a gait parameter recorded for the paretic limb, and $V_{\text{non-paretic}}$ is the corresponding value for the non-paretic limb. The magnitude of the index represents the degree of asymmetry, and the sign indicates the direction of asymmetry. An index of zero indicates perfect symmetry. A positive (negative) index indicates a larger value of the gait parameter for the paretic (non-paretic) limb. Since the direction of asymmetry was not always consistent across subjects in the hemiparetic and non-disabled groups, differences in the value of the index (asymmetry in Table 2) as well as its magnitude (asymmetry magnitude in Table 2) were assessed.

2.5. Statistics

The joint-kinematic and segmental-energetic trajectories and temporal-spatial gait variables in the hemiparetic and non-disabled subjects were visually examined for differences between speed-matched pairs. Because of the small sample size in this pilot study, full statistical analyses of the data were inappropriate. However, consistencies were tested using a Wilcoxon signed-rank test (significance set at $P < 0.10$). With $n = 6$ speed-matched pairs, the signed-rank test was significant at $P < 0.10$ only when either all six differences were in the same direction ($P = 0.03$), or 5 out of 6 differences were in the same direction with the non-conforming difference being the smallest ($P = 0.06$) or second

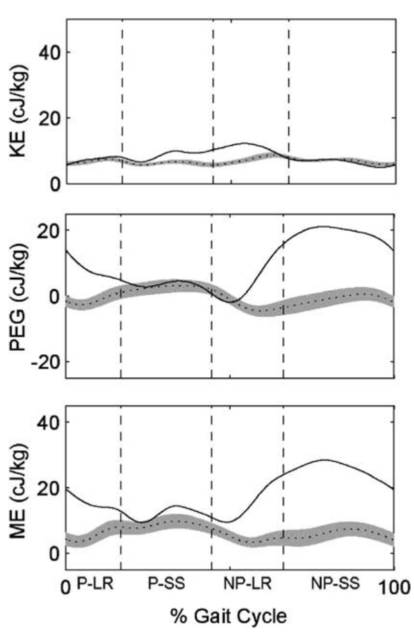

Fig. 1. Kinetic energy (KE), potential energy of gravity (PEG), and mechanical energy (ME = KE + PEG) of the whole body during the gait cycle for hemiparetic subject H2 (solid line) and non-disabled control N2 (dotted line, shaded region represent ±S.D. across gait cycles collected), beginning and ending with initial contact of the paretic limb (or side-matched limb in the control). Kinetic, potential, and mechanical energetic cost was defined to be the summed positive increments in these energies during a gait interval or stride. Note the large rise in ME and PEG during NP-LR and NP-SS in the hemiparetic subject. The increased cost was primarily attributed to an exaggerated increase in trunk height during pre-swing and swing of the paretic limb, consistent with pelvic hiking. Abbreviations: P-LR, paretic limb loading response; P-SS, paretic limb single support; NP-LR, non-paretic limb loading response; NP-SS, non-paretic limb single support. Vertical, dashed lines designate transitions between gait intervals for the hemiparetic subject.

Table 2
Temporal and spatial gait variables

	Hemiparetic	Non-disabled	P value
Gait cycles collected	10.0 (3.8)	11.5 (3.3)	
Speed (cm/s)	34.6 (11.7)	34.4 (11.7)	
Cadence (steps/min)	83.4 (12.8)	78.9 (21.7)	
Stride time (s)	1.47 (0.21)	1.63 (0.50)	
Stride length (cm)	52.3 (22.0)	53.3 (18.8)	
Step width (cm)	17.3 (5.9)	11.5 (2.2)	0.06
Swing time (% gait cycle)			
Paretic limb	39.8 (4.6)	32.2 (10.3)	0.06
Non-paretic limb	21.5 (4.5)	31.4 (8.4)	0.06
Asymmetry (%)	43.4 (16.5)	−0.1 (11.3)	0.03
Asymmetry magnitude (%)	43.4 (16.5)	6.7 (8.5)	0.03
Step length (cm)			
Paretic limb	29.8 (12.2)	27.8 (10.6)	
Non-paretic limb	22.4 (14.4)	25.4 (8.4)	
Asymmetry (%)	27.4 (56.3)	6.2 (11.6)	
Asymmetry magnitude (%)	48.0 (36.1)	11.3 (5.2)	0.09

Group means and standard deviations (in parentheses). Paretic and non-paretic limb variables are side-matched in non-disabled controls.

smallest in magnitude ($P = 0.09$). Thus, each of these three cases indicated strong and consistent differences between groups.

3. Results

Table 2 presents the group means for temporal and spatial gait variables for the hemiparetic subjects and non-disabled controls. Percentage swing time of the paretic limb was increased relative to values in side-matched limbs in non-disabled controls, and swing time of the non-paretic limb was reduced (both $P = 0.06$, Fig. 2). As a result, swing time asymmetry was greater in the hemiparetic group ($P = 0.03$). The magnitude of step length asymmetry was greater in the hemiparetic group ($P = 0.09$), though the direction of asymmetry was inconsistent across subjects.

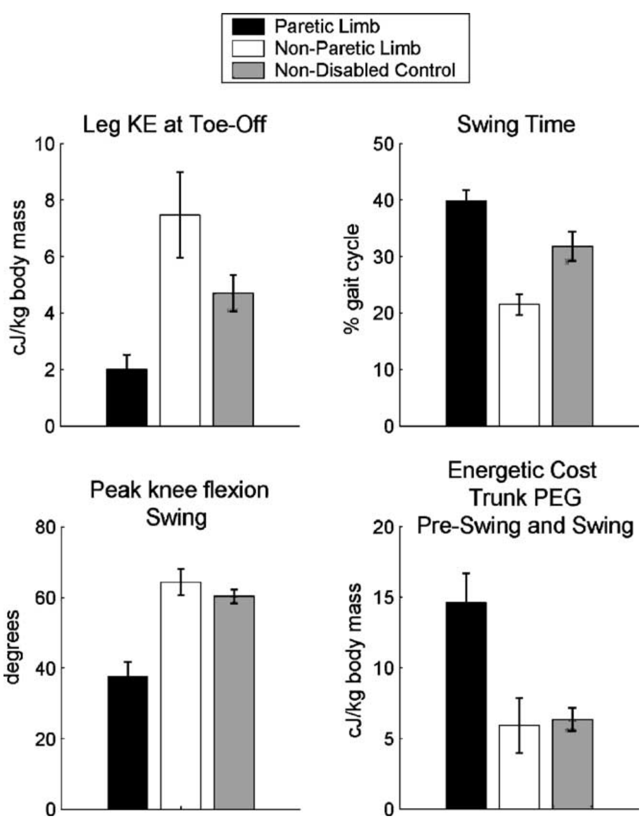

Fig. 2. Significant gait differences between hemiparetic and non-disabled subjects. Leg kinetic energy at toe-off, percentage swing time, peak knee flexion during swing, and energetic cost associated with rises in trunk potential energy during pre-swing and swing of the paretic limb (solid bars), non-paretic limb (white bars), and in non-disabled controls (gray bars). Values are means ± S.E. Means for non-disabled controls include both right and left limbs, since their gaits were very symmetrical. Leg kinetic energy at toe-off was reduced in the paretic limb compared to non-disabled controls, resulting in increased swing time and reduced peak knee flexion during swing. Leg kinetic energy at toe-off in the non-paretic limb was relatively high, resulting in shortened swing time. Energetic cost associated with raising the trunk during pre-swing and swing of the paretic limb was increased, consistent with pelvic hiking to clear the paretic limb with reduced knee flexion.

Table 3
Mechanical energetic gait variables

	Hemiparetic	Non-disabled	*P* value
Energetic cost – Stride interval (cJ/kg)			
Non-paretic limb pre-swing (P-LR)	8.5 (6.9)	8.2 (4.2)	
Non-paretic limb swing (P-SS)	3.8 (2.1)	3.5 (1.3)	
Paretic limb pre-swing (NP-LR)	12.5 (6.7)	6.6 (3.3)	
Paretic limb swing (NP-SS)	7.4 (5.2)	4.0 (1.6)	0.09
Total: Stride	32.3 (11.4)	22.5 (8.1)	0.06
Component energetic cost (cJ/kg)			
Trunk PEG in P-LR and P-SS	5.9 (4.7)	6.7 (3.6)	
Non-paretic leg KE in P-SS	2.6 (1.6)	1.8 (0.8)	
Trunk PEG in NP-LR and NP-SS	14.6 (5.0)	6.1 (2.1)	0.03
Paretic leg KE in NP-SS	4.8 (2.8)	1.8 (1.0)	0.03
Leg kinetic energy at toe-off (cJ/kg)			
Paretic limb	2.0 (1.2)	4.5 (2.0)	0.03
Non-paretic limb	7.5 (3.7)	4.9 (2.6)	0.09

Group means and standard deviations (in parentheses). Paretic and non-paretic limb variables are side-matched in non-disabled controls. Abbreviations: P-LR, paretic limb loading response; P-SS, paretic limb single support; NP-LR, non-paretic limb loading response; NP-SS, non-paretic limb single support; PEG, potential energy of gravity; KE, kinetic energy.

Table 3 presents the group means for mechanical energetic gait variables. Mechanical energetic cost per stride was greater in the hemiparetic group ($P = 0.06$), which was primarily attributed to increased cost during pre-swing (NP-LR) and swing (NP-SS) of the paretic limb. Potential energetic cost associated with raising the trunk during pre-swing (NP-LR) and swing (NP-SS) of the paretic limb and kinetic energetic cost associated with propelling the paretic limb during swing (NP-SS) were greater in the hemiparetic group (both $P = 0.03$, Fig. 2). Leg kinetic energy at toe-off was reduced in the paretic limb compared to non-disabled controls ($P = 0.03$), while leg kinetic energy in the non-paretic limb was greater than normal ($P = 0.09$) (Fig. 2).

Table 4 presents the group means for kinematic gait variables. Peak hip extension in the paretic limb was reduced in the hemiparetic group ($P = 0.09$). Knee flexion at toe-off and peak knee flexion during swing were greatly reduced in the paretic limb compared to non-disabled controls (both $P = 0.03$, Fig. 2). Foot lateral displacement during swing was greater in the paretic limb than in non-disabled controls ($P = 0.03$).

4. Discussion

Consistent gait differences existed between the hemiparetic subjects and non-disabled controls at matched speeds, even though the hemiparetic group was not uniform in terms of walking speed, AFO use, or side of hemiparesis. A large set of gait differences was consistent with impaired swing initiation in the paretic limb and related compensatory strategies. Leg kinetic energy at toe-off in the paretic limb was reduced, consistent with inadequate leg propulsion by

Table 4
Kinematic gait variables

	Hemiparetic	Non-disabled	*P* value
Hip joint angle			
Peak extension (°)			
Paretic limb	12.1 (10.0)	18.3 (5.4)	0.09
Non-paretic limb	16.6 (9.7)	18.4 (6.8)	
Knee joint angle			
Flexion at toe-off (°)			
Paretic limb	26.0 (3.8)	40.0 (5.9)	0.03
Non-paretic limb	48.5 (7.4)	40.6 (6.9)	
Peak flexion – swing (°)			
Paretic limb	37.8 (9.8)	58.6 (7.4)	0.03
Non-paretic limb	64.3 (9.3)	61.9 (6.4)	
Ankle joint angle			
Plantarflexion at toe-off[a] (°)			
Paretic limb	−5.5 (9.4)	−5.3 (7.3)	
Non-paretic limb	−3.7 (9.3)	−5.1 (7.0)	
Foot lateral displacement – swing (cm)			
Paretic limb	4.6 (3.2)	1.5 (0.5)	0.03
Non-paretic limb	1.6 (1.5)	1.5 (0.4)	

Group means and standard deviations (in parentheses). Paretic and non-paretic limb variables are side-matched in non-disabled controls.
[a] Negative values indicate ankle dorsiflexion.

the plantarflexors [14,15] or hip flexors [14,16] during pre-swing. As a result, energetic cost to propel the paretic limb during swing and percentage swing time in the paretic limb was increased (example data in Fig. 3). Since the generation of leg kinetic energy at toe-off is kinematically related to flexion of the knee during pre-swing (illustrated in Fig. 4), knee flexion at toe-off and peak knee flexion during swing in the paretic limb were also reduced. The exaggerated energetic cost associated with raising the trunk during pre-swing and swing of the paretic limb was consistent with pelvic hiking to compensate for reduced knee flexion during swing and contributed to increased mechanical energetic cost during walking (example data in Fig. 1). Moreover, increased lateral displacement of the foot during swing in the paretic limb was consistent with limb circumduction to further assist limb clearance.

A second set of gait differences between hemiparetic subjects and non-disabled controls was consistent with impaired single limb support on the paretic limb and related compensatory strategies. Propulsion of the non-paretic limb during pre-swing was exaggerated, resulting in increased leg kinetic energy at toe-off and reduced percentage swing time, consistent with weakness or poor balance during single limb support on the paretic limb (example data in Fig. 3). Knee flexion at toe-off in the non-paretic limb tended to be greater than normal, probably due to the exaggerated propulsion of the limb during pre-swing.

Other gait differences were observed between hemiparetic subjects and non-disabled controls. Step width was greater in the hemiparetic subjects, consistent with compensation for poor balance. Step length asymmetry was prominent in the hemiparetic group, but the direction of asymmetry was inconsistent across subjects. Four hemiparetic subjects exhibited a shorter step length in the non-paretic limb, and two exhibited a shorter step length in the paretic limb. Peak hip extension in the paretic limb was reduced in the hemiparetic group. The reduction was more evident in the subjects who exhibited shorter step length in the non-paretic limb, since their bodies did not displace as far forward of the supporting foot during paretic limb single support.

Some gait variables in the hemiparetic group were not consistently different from values in non-disabled controls. For instance, cadence, stride time, and stride length were not different. Ankle plantarflexion angles at toe-off in either limb were not different; neither were peak hip extension and knee flexion in the non-paretic limb. Moreover, energetic cost associated with the gait intervals corresponding to pre-swing and swing of the non-paretic limb was not different from values in non-disabled controls. Many of these vari-

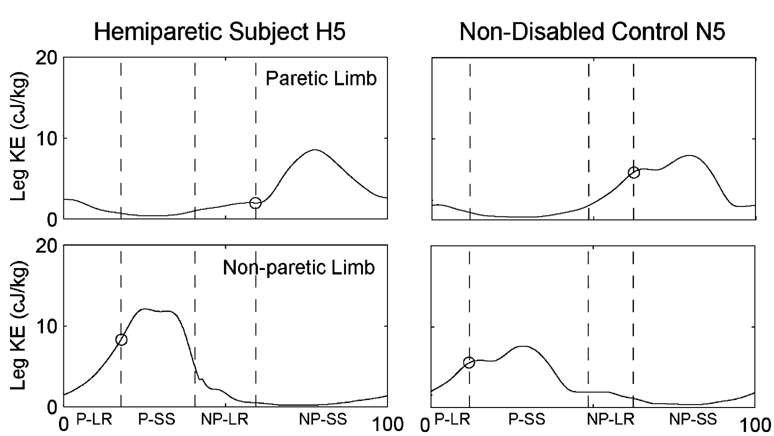

Fig. 3. Leg kinetic energy (KE) of the paretic and non-paretic limbs for hemiparetic subject H5 and side-matched limbs in non-disabled control N5 during the gait cycle, beginning and ending with initial contact of the paretic limb (or side-matched limb in the control). Note the lack of propulsion (i.e., rise in kinetic energy) in the paretic limb during pre-swing (NP-LR), resulting in low leg kinetic energy at toe-off (marked by circle), and subsequent propulsion of the limb during swing (NP-SS). In contrast, propulsion of the non-paretic limb was high during pre-swing (P-LR), resulting in increased leg kinetic energy at toe-off (marked by circle) and shortened swing time (P-SS). Abbreviations: P-LR, paretic limb loading response; P-SS, paretic limb single support; NP-LR, non-paretic limb loading response; NP-SS, non-paretic limb single support. Vertical, dashed lines designate transitions between gait intervals for each subject.

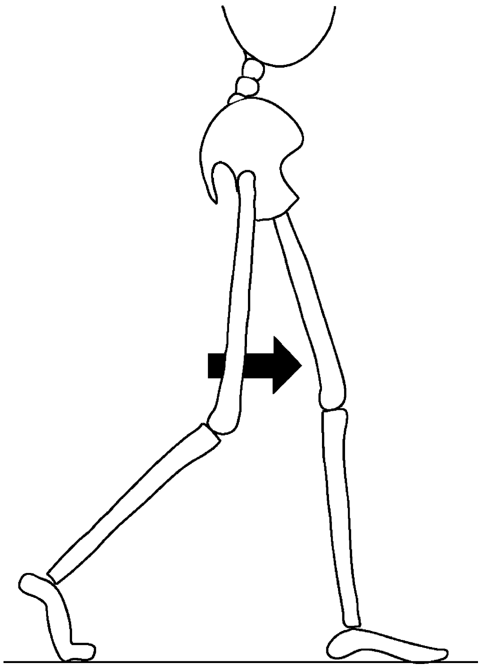

Fig. 4. Limb propulsion during pre-swing is the result of flexion of the knee, which propels the thigh and shank forward relative to the trunk and pivoting foot. (Adapted from Perry J. Gait Analysis: Normal and Pathological Function. Thorofare, NJ: Slack, 1992.)

ables were not consistently different because their values were similar to those in the non-disabled speed-matched controls. Other variables may have differed between matched subjects, but the directions of deviation were inconsistent. Further work is needed to assess gait deviations that are inconsistent across hemiparetic subjects and are specific to certain individuals.

In conclusion, consistent gait differences were found between the hemiparetic and non-disabled subjects at matched treadmill speeds. Moreover, the speed-matched comparisons allowed the identification of interrelationships between biomechanical variables and deviations in both the paretic and non-paretic limbs. A large set of gait differences was consistent with impaired swing initiation and single limb support in the paretic limb and related compensatory strategies. These findings should be substantiated in a larger group of hemiparetic subjects and non-disabled controls.

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