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Kinematics, kinetics and muscle activities of the lower extremity during the first four steps from gait initiation to the steady-state walking [†]

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Abstract

In this study, biomechanical characteristics during the whole process of gait initiation for twenty normal healthy volunteers were determined by the motion analysis with six near-infrared cameras, four forceplates, and an EMG system. Gait initiation, a transitional movement phenomenon from quiet stance to steady-state walking, involves a series of muscular activities, GRFs, movements of COP and COM, and joint motions. Results showed that the location of the net COP to be most lateral during double limb stance at the beginning of gait initiation. During gait initiation, changes in anteroposterior components of GRFs were first found and then changes in vertical components followed. Hip and knee motions were found before the ankle joint motion. Walking speed, step length, and stride length gradually increased until the second step. The interaction between the COM and COP is tightly regulated to control the trajectory of the COM and thereby control total body balance.

Keywords: Gait initiation; Movement of COP and COM; Joint motion; Electromyography

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1. Introduction

Gait initiation, a transient phase between standing and walking, is a complicated process with the neuromusculoskeletal systems to control the body against a perturbated situation [1]. There are many reports that falls occur most frequently in persons with poor score in clinical tests, emphasizing transfer for quasi-static to dynamic situations [2].

Carlsoo [3] studied muscle activations and ground reaction forces during gait initiation. Mann et al. [1] measured ground reaction forces (GRFs) and electromyography (EMG) on eight muscles in the lower extremity during gait initiation experiment and reported that the center of pressure (COP) moved laterally and posteriorly toward the leading limb in the beginning. However, unfortunately, they regarded that the trajectory of COP during gait initiation was a projection of the anteroposterior and mediolataeral movements of the center of gravity (COG). Cook and Cozzens [4] measured EMG signals on healthy young volunteers and found that walking speed increased during gait initiation with the increased activity of tibialis anterior (TA) muscles. Brenier et al. [5-7] used measured GRFs during gait initiation using forceplates and reported that shear components of the GRFs reflected on anteroposterior and mediolateral accelerations of COG. However, most of previous studies that analyzed GRF of the trailing limb and muscle activities [8-10] include GRF, EMG signals, and joint angles of the lower extremity only from the double limb upright standing position until toe off (TO) of the trailing limb.

Breniere et al. [5] used a forceplate and studied

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Table 1. Subjects in this study.

(N=20)

			Mean±Std	Range
Age		(yrs)	24.6±2.01	21~28
Height		(cm)	174.2±4.45	166.5~183
Weight		(cm)	70.3±5.82	63.0~84.0
Pelvic width		(cm)	26.2±1.61	23.4~28.6
Leg length	Left	(cm)	87.5±4.14	82.0~94.3
	Right	(cm)	87.3±4.46	81.3~95.3
Knee width	Left	(cm)	9.53±1.10	8.1~11.6
	Right	(cm)	9.56±0.98	7.9~11.4
Ankle width	Left	(cm)	6.60±0.35	6.1~7.1
	Right	(cm)	6.47±0.39	5.9~7.0

movements of both COG and COP until TO of the leading limb, assuming that the steady-state walking is started from the second step. Thus, their results were different from others [1, 4] who assumed that at least 2~3 steps were required to reach the steady-state walking speed during gait initiation process. Later, Jian et al. [11] used three forceplates to analyze COG movements for the whole process of gait initiation. They revealed that 90% of steady-state velocity was achieved during the first step and 100% by the second step. However, they did not analyze GRFs and joint moments and powers during the whole process of gait initiation.

Therefore, in this study we tried to determine bio-mechanical characteristics such as spatial-temporal gait parameters, COP movements, joint angles, and EMG during the whole process of gait initiation.

2. Methods

Twenty normal healthy male volunteers who had no history of neuromusculoskeletal disorders for walking were selected for the subjects in this study (Table 1).

Six near-infrared cameras (Vicon 612 Motion Analysis System, Oxford Metrics, UK) were used to determine joint motions during gait initiation. In addition, GRFs and muscle activities of the lower extremities were also synchronously measured using four forceplates (2 AMTI forceplates, Watertown, MA, USA, 2 Kistler forceplates, Switzerland) and a dynamic EMG system (MA 300, Motion Lab., USA).

In order to measure joint motions of the lower extremity, sixteen reflective markers of 14mm diameter

Fig. 1. Subjects who had reflective markers and EMG electrodes for the gait motion experiment.

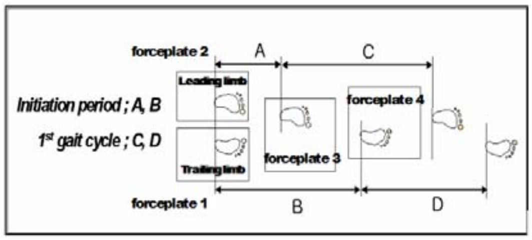


Fig. 2. The arrangement of four forceplates.

were attached on the anatomical locations based on both anterior superior iliac spines, posterior superior iliac spines, thighs, knees, shanks, lateral malleoli, second metatarsal heads, and heels based on the Helen Hayes marker set [12]. Movements of the net COP were calculated using the GRFs measured by the force platforms during gait initiation. Surface EMGs were also measured on both sides of tibialis anterior, rectus femoris, gastrocnemius lateralis, biceps femoris, and gluteus medius.

Fig. 2 shows the arrangement of four forceplates (forceplate 1, 2, 3, and 4) for this study. Gait patterns in four gait periods (A, B, C, and D) were compared with the steady-state walking of the same subject.

For each subject, ten trials of the steady-state walking were performed first, and then fifteen trials of the gait initiation experiments were followed. Sufficient gait exercises were done before the actual measurements. Upright standstill posture, defined by when there were less than 0.5% of the half of the subject's body weight for two seconds were regarded as the onset of the gait initiation. A represents the interval until the initial contact (IC) of the leading limb from the onset of the gait initiation and C is the next gait cycle of the same limb. On the other hand, B is the interval until the IC of the trailing limb from the onset

Table 2. Spatial-temporal parameters in gait initiation and in the normal steady-state walking.

(N=20)

		Cadence (steps/min)	Foot off (%)	Step length (m)	Step time (s)	Stride length (m)	Stride time (s)	Walking speed (m/s)
Gait initiation	Leading limb	-	71.6±2.44	0.60±0.05	1.39±0.05	0.61±0.05	1.39±0.05	0.44±0.03
	Trailing limb	-	78.0±1.02	0.64±0.03	0.60±0.03	1.26±0.05	2.00±0.06	0.63±0.03
1st gait cycle	Leading limb	105±4.83	62.8±1.38	0.69±0.05	0.54±0.03	1.35±0.07	1.15±0.05	1.18±0.07
	Trailing limb	112±5.10	60.6±1.48	0.69±0.04	0.53±0.03	1.38±0.07	1.08±0.05	1.28±0.08
Steady-state walking		118±4.64	59.6±1.01	0.70±0.04	0.51±0.02	1.40±0.07	1.02±0.04	1.37±0.09

of the gait initiation, and D represents the next gait cycle of the trailing limb. In this study, the left leg was decided as the leading limb, since there were no significant differences of the leading limb [13].

COP during single-limb support period was calculated directly from GRFs acting on a force plate. In addition, the net COP during double-limb support period was determined from the coordinates of COP using the GRFs measured by the forceplates the following equation.

$$COP_{net(x,y)} = COP_{l(x,y)} \frac{F_{z,l}}{F_{z,l}+F_{z,t}} + COP_{t(x,y)} \frac{F_{z,t}}{F_{z,l}+F_{z,t}}$$

$COP_{l(x,y)}$: COP of the leading limb
$COP_{t(x,y)}$: COP of the trailing limb
$F_{z,l}$: Vertical GRF on the leading limb
$F_{z,t}$: Vertical GRF on the trailing limb

Dynamic EMG data was filtered by the Butterworth 4th-order filter (30-500Hz) and RMS values were taken every 100ms.

3. Results

3.1 Spatial-temporal gait parameters

Table 2 represents spatial-temporal parameters in gait initiation and in the normal steady-state walking respectively. After the gait initiation period, all parameters in the first gait cycle approach to the ones in the normal steady-state walking, even though there were still significant differences in magnitudes.

3.2 Trajectory of the net COP

GRFs on both limbs affect the location of the net

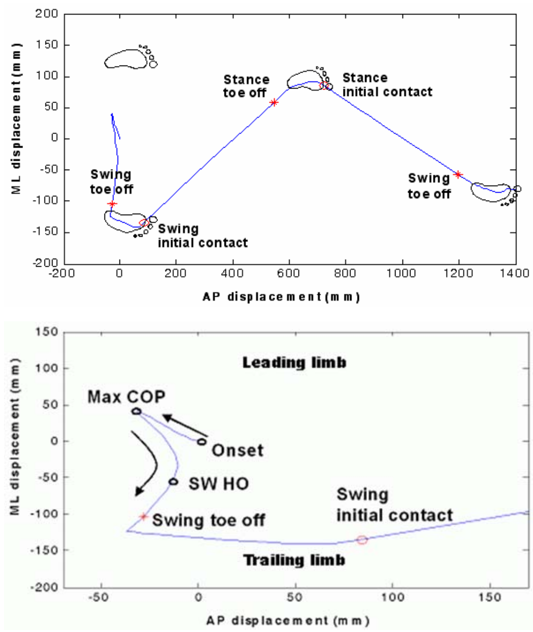
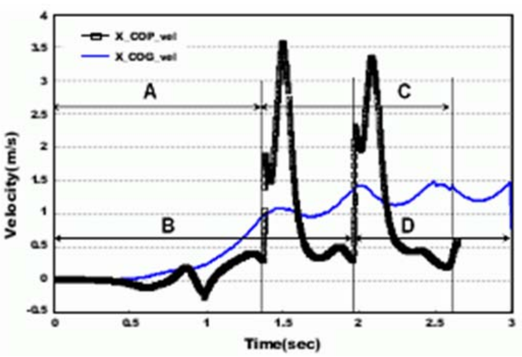


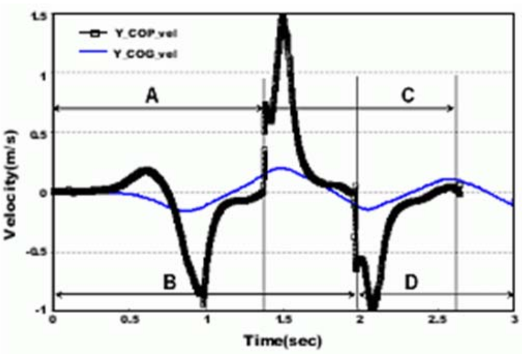
Fig. 3. Movement of the net COP during gait initiation.

COP. Fig. 3 represents the entire path of the net COP especially during the period from “A” to “D” and the trajectories of the net COP during gait initiation. At the onset of the gait initiation, COP moves laterally and posteriorly with a relatively slow speed. At the very beginning of gait initiation ("A" and "B"), GRFs on the leading limb relatively increase and become the local maximum, which causes the location of the net COP to be most lateral during the double limb stance. Just after both GRFs become equal, the net COP moves quickly toward the trailing limb and heel off (HO) of the leading limb takes place. From HO to toe off (TO) of the leading limb, the net COP moves laterally and posteriorly with a relatively fast speed. During the single support period of the trailing limb, the net COP slowly moves laterally and anteriorly. At the very beginning of gait initiation the toe width is larger than that in the normal walking, the magnitude of mediolateral movements of the net COP decreases once gait initiates. The COP moves faster during double support period than during single limb support period.

Fig. 4(a) represents the anteroposterior velocity of the COP and the COG during gait initiation. The COG was calculated by the centroid of four pelvic markers (LASIS, RASIS, LPSIS, and RPSIS). It is noted that the maximum anteroposterior velocity of the COP is much larger than that of the COG especially just after IC. It is also noted that the maximum COP velocity in "D" is smaller than that in "C". Fig. 4(b) represents the mediolateral velocity of the COP and the COG during gait initiation. At TO of the leading limb, the mediolateral velocity quickly increases. Again, the maximum mediolateral COP velocity in "D" is smaller than that in "C".



(a) Anteroposterior



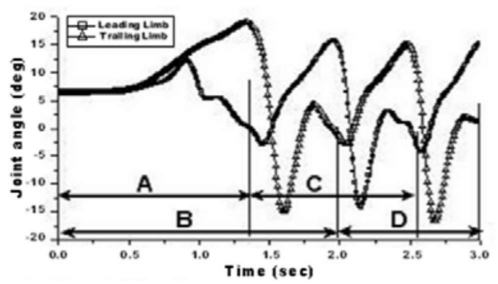
(b) Mediolateral

Fig. 4. COP velocities during gait initiation.

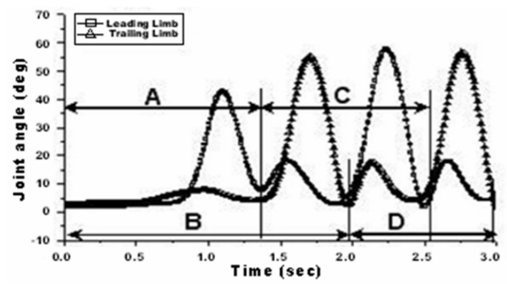
3.3 Joint angle

Fig. 5 represents sagittal plane angles of the ankle, knee, and hip joints during gait initiation. At the upright stance position before gait initiation, ankle, knee, and hip joints were slightly flexed. At the onset of gait initiation (interval "A"), the ankle joint of the leading limb showed no plantarflexion until TO when it was dorsiflexed at 12.7°. There was no stance phase knee flexion in the leading limb, but the maximum swing phase flexion after TO was approximately 46.9°. The maximum knee flexion of the leading limb was considerably smaller, but the maximum hip flexion was larger than those in the normal walking.

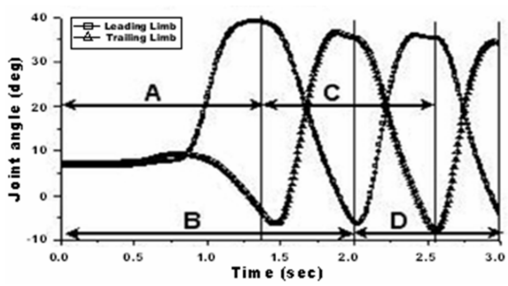
During the interval "B", the ankle joint of the trailing limb showed 19.8° dorsiflexion at HO without



(a) Ankle



(b) Knee



(c) Hip

Fig. 5. Sagittal plane angles of ankle, knee, and hip joints.

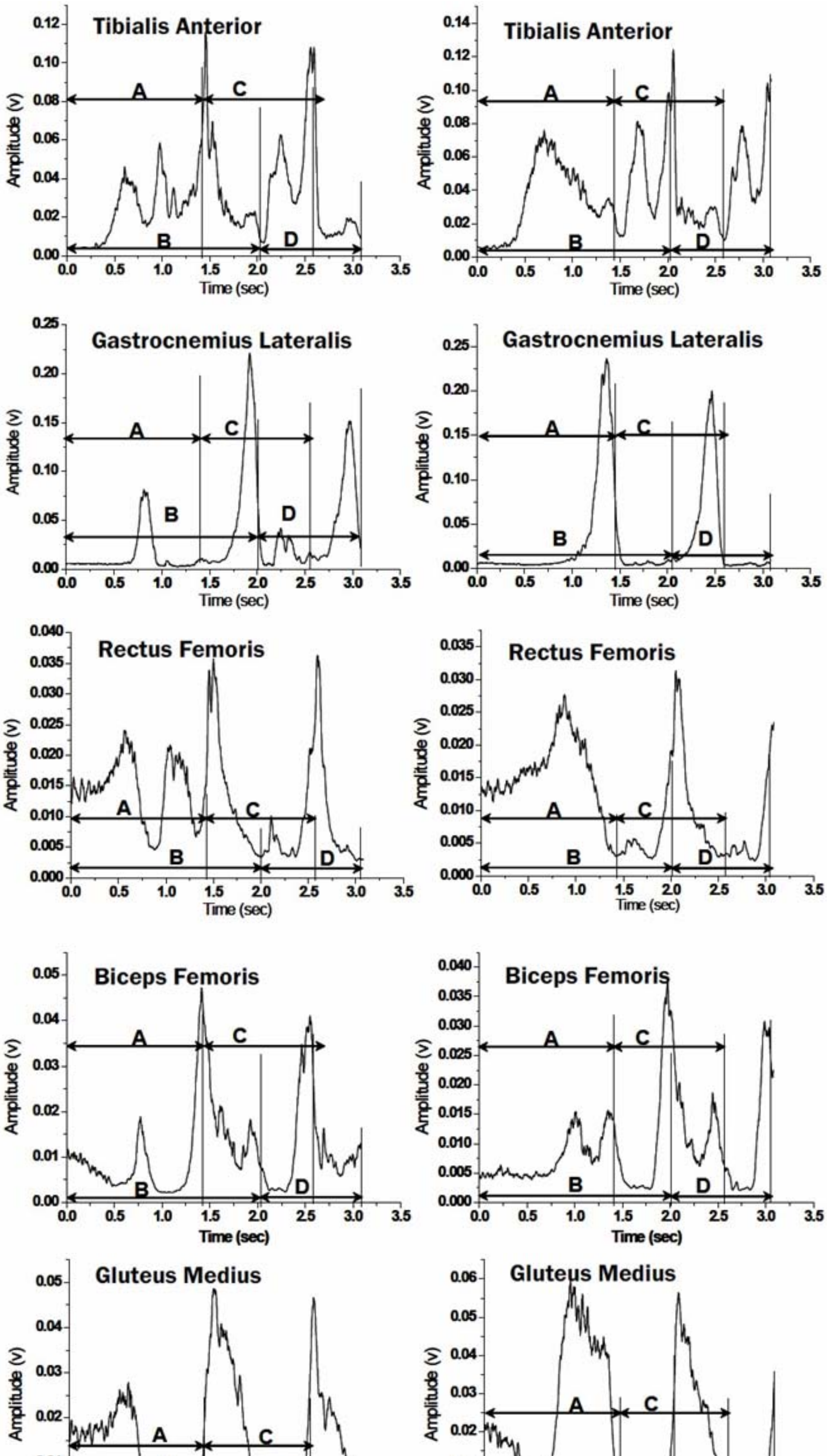


Fig. 6. EMG signals of TA, GCL, RF, BF, and GM.

initial plantarflexion, which was significantly larger than that in the normal walking. There was a small knee flexion in stance and the maximum knee flexion in swing phase was approximately 56.8°, which was about 93.7% of the normal walking. A slight hip flexion (approximately 5°) was shown during stance and the maximum hip extension of the trailing limb was 8.9° which was about 88.1% of the normal walking. The maximum hip flexion during swing phase of the trailing limb was about 34.5°, which was larger than that in the normal walking.

During the interval "C", the maximum dorsiflexion of the leading limb in stance significantly delayed compared with that in the normal walking. The knee joint was slightly flexed by 9.3° at IC of the leading limb and the stance phase knee flexion was about 18.2°. The Hip joint of the leading limb was also flexed by 9.3° at IC. The maximum hip extension was also delayed by approximately 4%. During the interval "D", joint angles of hip, knee, and ankle looked similar to those in the normal walking.

3.4 Electromyography

Fig. 6 shows EMG signals of both tibialis anterior (TA), gastrocnemius lateralis (GCL), rectus femoris (RF), biceps femoris (BF), and gluteus medius (GM) during the whole gait initiation process. When both limbs were in upright standing position before gait initiation, BF, RF, and GM were contracted [14]. However, once the gait initiated, BF and GM relaxed and TA contracted. Just before the net COP arrived at the most lateral location, both BF and GM relaxed but RF and GCL contracted. In order to lift the leading limb for gait initiation, GCL and BF relaxed but TA and RF contracted.

While RF and GM of the leading limb contracted, TA of the leading limb began to contract and GM of the trailing limb relaxed. The contraction of TA of the leading limb corresponded to the increase in anteroposterior GRFs, but the contraction of GM of the trailing limb was followed by increases in the medial component of GRFs. At HO of the leading limb, the relaxation of GCL and BF and the contraction of TA and RF resulted in knee flexion at HO of the leading limb. The contraction of TA and the relaxation of RF continued during swing phase. IC was prepared by the contraction of BF at terminal swing. TA continued to contract until midstance during the interval "C". At HO of the trailing limb, GCL and BF simultaneously contracted to extend the knee and accelerate the body forward, and GM of the trailing limb relaxed and RF of the leading limb contracted just before IC of the leading limb. BF and RF of the leading limb which was contracted at IC continued to activate until TO of the trailing limb.

4. Discussion

Gait initiation, a transitional movement phenomenon from quiet stance to steady-state walking, involves the series of muscular activities, GRFs, movements of COP and COM and joint motions. During quiet stance position, GRFs acts medially with respect to the ankle joint. During gait initiation, changes in anteroposterior components of GRFs were first found and then changes in vertical components followed. After the change in GRFs, hip and knee motions followed before the ankle joint motion. Our results agreed with the previous study [15], reporting that the change in GRFs occurred 300ms before the knee flexion of the leading limb. In addition, Brunt et al. [8] also supported the present results in the fact that gait initiation from quiet stance involves active isometric muscle contractions.

During quiet stance period, GCL contracts and COM locates 2-9cm anterior to the ankle joint [14]. The movement of COP in the sagittal plane is controlled by the interaction between the agonist and antagonist muscles [16]. Both the rel-axation of GCL and the contraction of TA resulted in the posterior movement of COP, and the contraction of GM of the leading limb and the relaxation of GM of the trailing limb made COP move toward the leading limb [9, 14]. This study also supported that during gait initiation, muscular activities of TA and GCL are in the opposite phase each other [14]. Crenna et al. [17] and Cook et al. [4] reported that TA contraction increased as the walking speed increased from quiet stance, which was not true in our study. Mediolateral movements of the COP also well controlled with the muscular activities of GM, hip abductor muscles. COP moved toward the trailing limb as GM of the leading limb relaxed slowly and GM of the trailing limb contracted.

Previous study [16] emphasized that the anteroposterior component of GRFs was not important during gait initiation due to the smaller magnitude. However, our study revealed that the magnitude of the mediolateral GRFs were about 53% of anteroposterior components. For people with Parkinson's disease or hemiplegia has larger mediolateral but smaller anteroposterior movements [18]. Therefore, mediolateral GRFs should be also considered in some pathological gait initiation.

5. Conclusion

In this study, we determined biomechanical characteristics such as spatial-temporal gait parameters, GRFs, COP movements, joint angles, and EMG during the whole process from the gait initiation to the steady-state walking. Decreased walking speed, step length, and stride length gradually increased until the second step. Compared with the normal walking, hip joint of the leading limb was more flexed at terminal swing and the ankle joint of the trailing limb also increased during terminal stance. All joint motions of the lower extremity slightly delayed. During gait initiation, anteroposterior GRFs of the leading limb changed first then vertical GRFs changed next. For the leading limb during gait initiation, changes in GRFs occurred earlier than those in joint angles. For the trailing limb during gait initiation, ankle motions were followed by knee and hip motions. The interaction between the COM and COP is tightly regulated to control the trajectory of the COM and thereby control total body balance.

Further studies on hemiplegic patients and amputees would differentiate many biomechanical parameters in the normal gait initiation process.

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