Motion Analysis on Backward Walking: Kinetics, Kinematics, and Electromyography

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Motion Analysis on Backward Walking: Kinetics, Kinematics, and Electromyography

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Abstract

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Backward walking (BW) is a recently emerging exercise. Researches in human walking have classified BW as a reversible movement. Researchers have asserted that joint motions of forward walking (FW) at the hip and ankle are similar to the time-reversed counterpart of BW (heel off). However, there has been a lack of research on the kinematic and kinetic aspects of BW relative to research on FW. Though some kinematic analyses of BW have been made, the lack of research on BW (heel off) lies prominently in its kinetic analysis. Hence, this study has adopted the atypical design: it analyzed the kinetics of BW. Thus the present paper identified the mechanism of BW (heel off) through kinetic analysis, especially on BW (heel off)'s time-reversed data and electromyography data. Thirty-one healthy subjects participated in this study. A six-camera 3D motion analysis system was used to acquire three-dimensional data of joint movements during walking. Surface EMG was used to collect the raw EMG data using a Trigno wireless system. Ground reaction force (GRF) curves were acquired from four piezoelectric force plates camouflaged within a 5-m walkway. Each subject performed ten FW trials and forty BW (heel off) trials with bare feet. For both type of trials, stride characteristics, marker coordinates, electromyography data, and GRFs were recorded simultaneously. Data pairs acquired from the markers and force plates were used to calculate joint angles, moments, and powers through the Plug-In-Gait Biomechanical Modeler pipeline. To follow the purpose of this study, which is to compare the kinematic and kinetic patterns of FW and BW (heel off), curves of BW (heel off)'s joint angles and joint moments were time-reversed to equalize the contact position as well as the type of event. Sixteen gait parameters generated and analyzed using a paired t-tests ($p<0.05$). The angular and moment patterns of time-reversed BW (heel off) and FW were statistically significant. The data of EMG and joint powers is also used to analyze the muscle activation during BW (heel off), however, this showed great differences with previous studies. This study identified the gait mechanism of BW (heel off), and successful results in current and future research in the kinetic and kinematic data of BW (heel off) will establish a fundamental mechanism of BW (heel off).

Key words **:** Backward walking, normal gait, electromyography, gait analysis, motion capture

1. Introduction

Backward walking (BW) (Figure 1.1) is a recently emerged exercise. Adopting the motor/system control perspective, researches in human walking have classified the aforementioned retro-locomotion as a member of “reversible movements.” Researchers have asserted that joint motions of forward walking (FW) especially at the hip and ankle are similar to the time-reversed counterpart of BW [1-11]. On the other hand, researchers differ in their statements on the muscle activation during BW. Thorstensson et al. [9] and Grasso et al. [10] reported that the EMG patterns of muscle activity in BW showed a poor relation to those in FW. The primary factor that created the difference was the origin of propulsion; while the main FW propulsion is provided by the ankle plantarflexors, the main BW propulsion is provided by the hip and knee extensors [10]. Muddasir et al. showed that BW decreases the angle between the hip and the knee and increases the angle of the ankle joint [11]. To recapitulate, contrary to the results of kinematic analyses between BW and FW, EMG studies have identified differences between the patterns of BW and FW.

However, limited amount of researches exists regarding motion analysis in BW, compared with that in FW. Though some kinematic analyses of BW have been made, the lack of research on BW lies prominently in its kinetic analysis. Hence, this study has adopted the atypical design: it analyzed the kinetics of BW. However, as BW is an instinct of human locomotion based on FW, studies in BW have substantial potential for understanding the control of human locomotion behavior [7].

Thus, the present study identifies the mechanism of BW through kinetic analysis, especially on BW's time-reversed data and EMG data. It focuses on comparing BW's spatiotemporal parameters and time-reversed data of kinematics and kinetics to those of non-reversed FW with prospects of results contributive to approaching the mechanism of gait during BW.

2. Methods

2.1 Participants

Thirty-one healthy subjects of age 22.4 ± 3.2 years old, height 171.5 ± 5.5 cm, and weight 70.0 ± 10.4 kg participated in this study (Table 2.1). Comprising twenty six males and five females, the subjects had no evidence or history of lower-limb diseases, nor any record of surgery to the lower limbs. All subjects gave informed consent before participating in the experiments.

Table 2.1 General information of participants (n=31)

			Avg.	**±**	**S.D.**		**Range**	
Age		(yrs)	22.4	±	3.2	18	~	32
Weight		(kg)	70.0	±	10.4	54.1	~	93.4
Height		(cm)	171.5	±	5.5	158	~	182
Leg length	Left	(cm)	88.6	±	3.5	82	~	96
	Right	(cm)	89.2	±	3.6	83	~	97
Knee width	Left	(cm)	11.4	±	1.0	9.4	~	13.8
	Right	(cm)	11.4	±	1.0	9.5	~	13.7
Ankle width	Left	(cm)	7.4	±	0.5	6.5	~	8.5
	Right	(cm)	7.4	±	0.5	6.4	~	8.8

Avg. : Average, S.D. : Standard Deviation

2.2 Instruments

A 3D motion analysis system (VICON612, Motion Systems Ltd., Oxford, UK) using six infrared cameras was used to acquire three-dimensional data of joint movements during walking. The calibration of the system was performed before gait trials. Sixteen retro-reflective markers (14 mm diameter) were attached with double-sided tape on the subjects' lower limb according to the Plug-In-Gait (PIG) model (Oxford Metrics, UK, Figure 2.2). Motion data were collected at 120 samples per second. All marker coordinates were smoothed with the Woltring filter (MSE = 15).

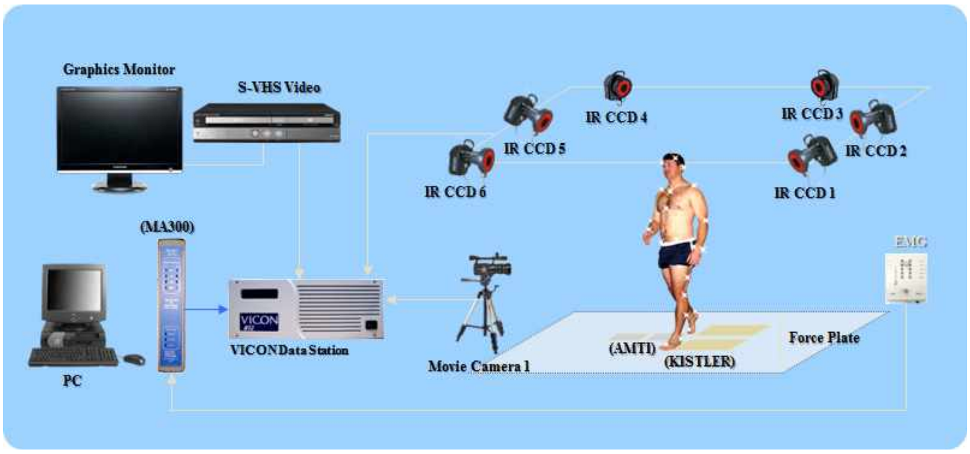


Figure 2.1. Three-dimensional motion analysis system (VICON612)

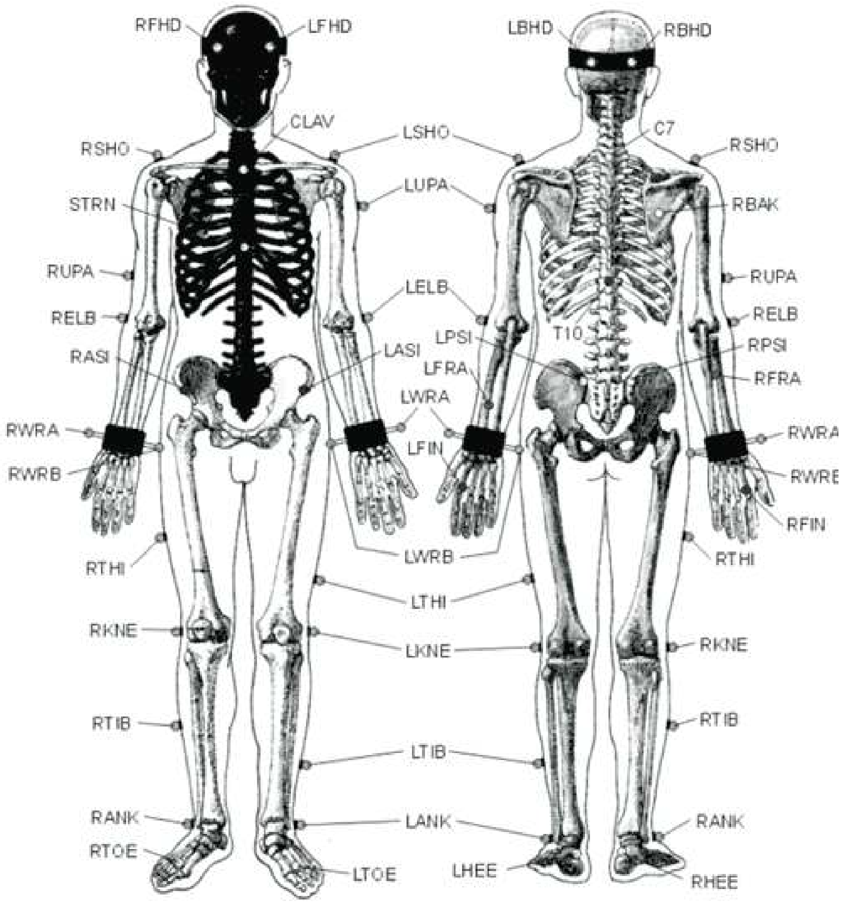


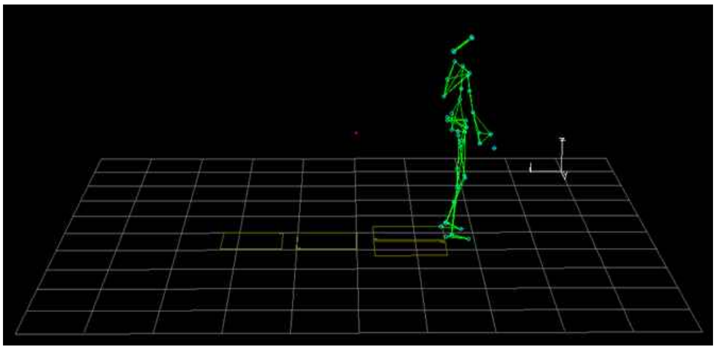
Figure 2.2. Plug in gait marker set

Trigno wireless EMG system (Delsys, USA) was used to determine muscle activities during walking. The signals were amplified and band-pass filtered (20-450Hz) before being digitally recorded at 1000 samples/s. The EMG signal was transformed into a linear envelope through full-wave rectification and filtered using the second-order Butterworth filters (6Hz). Eight surface electrodes (Trigno sensors; Delsys, USA) were placed on the following muscles on the dominant (right) side: tibialis anterior, gastrocnemius, soleus, rectus femoris, vastus medialis, vastus lateralis, biceps femoris and gluteus maximus. The skin was prepared before attaching the electrodes by shaving site and cleaning with alcohol to reduce the skin impedance [12].

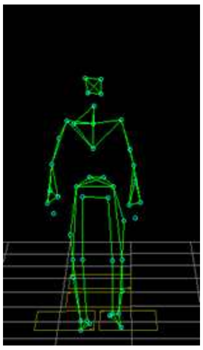
Ground reaction force (GRF) curves were acquired from two Kistler (5233A2, Kistler, Switzerland) and two AMTI (OR6-6, AMTI, USA) force plates. The GRF data were sampled at 1080 Hz. All measurements were synchronized in time.

2.3 Procedures

Before the gait analysis, the subjects' age, height, weight, and lower-extremity anthropometric data were measured. Each subject performed ten FW trials and forty BW (heel off) trials with bare feet. For both type of trials, stride characteristics, marker coordinates, EMG data, and GRFs were recorded simultaneously. The subjects practiced BW (heel off) prior to the actual experiments for successful adaptation to the new environment and walking pattern. To reflect their natural stride length and unique gait characteristics, subjects were required to walk with comfortable paces without knowing the position of the force plates.



(a)



(b)

Figure 2.3. Three-dimensional motion capture according to PIG
(a) Sagittal plane (b) Coronal plane

To normalize the EMG signal, the reference voluntary contraction (RVC) exercise was performed before the experiments (Figure 2.4). For each reference exercises, the peak amplitude (two peaks were mostly observed for biceps femoris in which case the first peak was used, whereas a single peak was observed for other muscles) during concentric contraction was measured in 5 trials, excluding the first trial, and the average value was used as the 100% reference value [13].

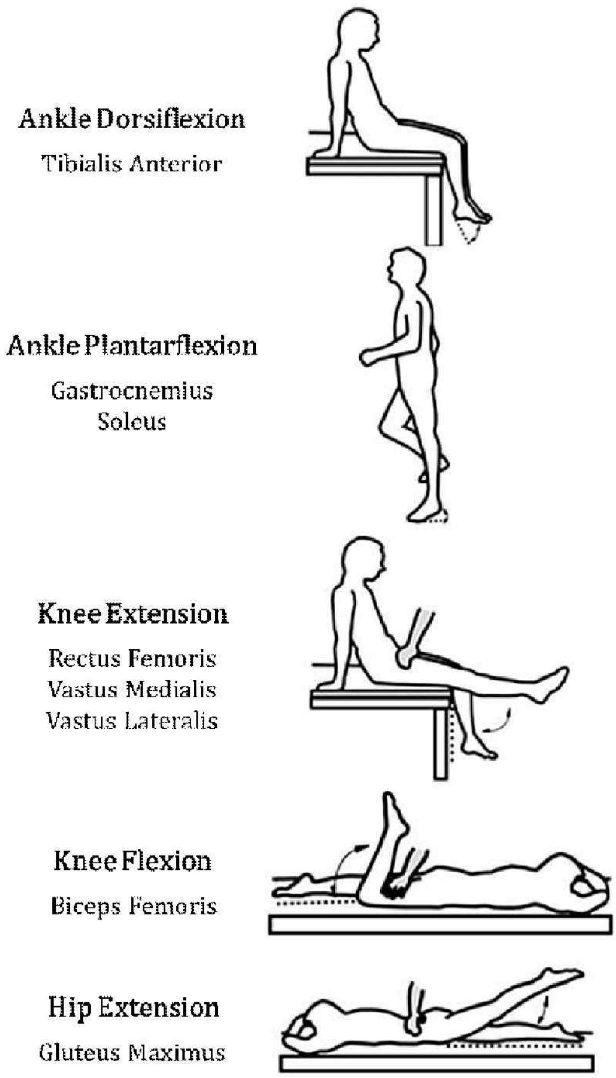


Figure 2.4. Body positions and muscles tested in reference exercises

2.4 Data analysis

Data pairs acquired from the markers and force plates were used to calculate joint angles, moments, and powers through the Plug-In-Gait Biomechanical Modeler pipeline (Oxford Metrics, Oxford, UK). Spatiotemporal parameters were computed from the marker coordinate data using a developed code (MATLAB, MathWorks Inc., USA).

Gait patterns of BW were divided into two groups; toe contact to heel off group, BW (heel off), and toe contact to toe off group, BW (toe off) (Figure 2.5). FW consists of heel contact to toe off, which means that FW and BW (heel off) had opposite contact positions (toe or heel) for the same event (contact or off).

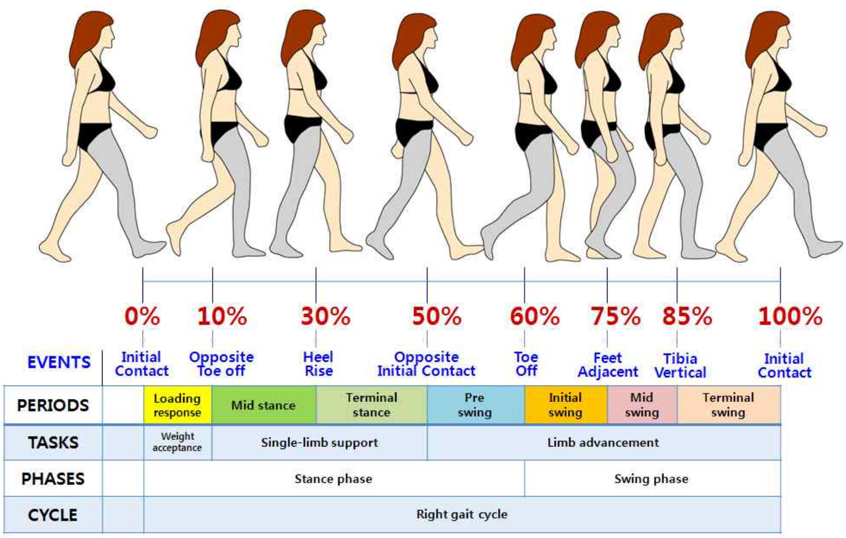


Figure 2.5. Events, periods, tasks, and phase of the gait analysis

To follow the purpose of this study, which is to compare the kinematic and kinetic patterns of FW and BW, curves of BW (heel off)'s joint angles and joint moments were time-reversed to equalize the contact position as well as the type of event. First, the whole stance phase was reversed. Then the remaining gait cycle, the swing phase, was reversed to form a whole new gait cycle with each phase reversed. BW (heel off)'s GRF curves were not time-reversed because they are affected more by the participant's body weight than gait event itself [14]. Crucial points among joint angles, moments, and vertical GRF curves were chosen as gait parameters [15]. To analyze the differences in BW group, non time-reversed curves of BW (heel off) and BW (toe off) were compared.

Gait cycles were normalized entirely from 0 % to 100 % of the gait cycle to clearly distinguish both major and minor variations in the patterns of any individual trial [16]. Spatiotemporal parameters, kinematics, kinetics, and GRF data were determined from each subject during both forward and backward level walking. Sagittal plane motions were analyzed as the majority of the forces and motions occur in these planes [17].

For each subject, EMG values each representing one gait cycle were normalized with respect to the time (100% stride) obtained from FW and BW trials. The EMG signals were used to calculate percentage RVC (%RVC) and then averaged [19].

2.5 Statistical analysis

Sixteen gait parameters were generated (Table 2.2). Paired t-tests ($p<0.05$) were used to detect significant differences in gait parameters. K3, knee and hip joint moment, and power parameters were excluded due to the difference of gait mechanisms between FW and BW [10], which will be elaborated in the result of this paper. The spatiotemporal parameters were also analyzed using paired t-tests ($p<0.05$) to verify the significant differences between forward and backward walking (heel off). All data were analyzed with SPSS 19, statistical software.

Table 2.2 Gait parameters of ankle, knee, and hip joint

	Ankle Joint Variable
A1	Flexion at heel strike
A2	Max. plantarflexion at loading response
A3	Max. dorsiflexion in stance phase
A4	Max. plantarflexion in swing phase
A5	Total range of motion
AM1	Max. plantarflexion moment
AM2	Max. dorsiflexion moment
AP1	Max. power generation
AP2	Max. power absorption

	Knee Joint Variable
K1	Flexion at heel strike
K2	Max. flexion at loading response
K4	Max. flexion in swing phase
K5	Total range of motion

	Hip Joint Variable
H1	Flexion at heel strike
H2	Max. extension in stance phase
H3	Total range of motion

3. Results

3.1 Stride characteristics

Significant reductions in walking speed (1.3 ± 0.1 m/s vs. 1.1 ± 0.1 m/s, P<.001) and cadence (111.4 ± 5.2 steps/min vs. 98.1 ± 8.1 steps/min, P<.001) were observed in BW (heel off), comparing with FW. However, stance phase % (60.1 ± 1.4 % gait cycle vs. 60.4 ± 1.6 % gait cycle, P=.321) and swing phase % (39.9 ± 1.4 % gait cycle vs. 39.6 ± 1.6 % gait cycle, P=.321) showed no significant difference. Stride time (1.1 ± 0.1 s vs. 1.2 ± 0.1 s, P<.001) showed significant increases during BW (heel off). Stride length also significantly different between BW (heel off) and FW (1.4 ± 0.1 m vs. 1.3 ± 0.1 m, P<.001) (Table 3.1).

Table 3.1 Stride characteristics; FW vs. BW (heel off)

Stride characteristics	**Forward walking**			**Backward walking (Heel-off)**			***P***
	Avg.	**±**	**S.D.**	**Avg.**	**±**	**S.D.**	
Walking speed (m/s)	1.3	±	0.1	1.1	±	0.1	<.05*
Cadence (steps/min)	111.4	±	5.2	98.1	±	8.1	<.05*
Stance phase percentage in gait cycle (%)	60.1	±	1.4	60.4	±	1.6	>.05
Swing phase percentage in gait cycle (%)	39.9	±	1.4	39.6	±	1.6	>.05
Stride time (s)	1.1	±	0.1	1.2	±	0.1	<.05*
Stride length (m)	1.4	±	0.1	1.3	±	0.1	<.05*

3.2 Kinematics

3.2.1 Ankle joint angles

The ankle showed significantly less plantarflexion and greater dorsiflexion during BW (heel off) than during FW for the whole gait cycle (A1 - A4, P<.001; Figure 3.1). During BW (heel off), the ankle had 4.2° of plantarflexion during the loading response. The difference between FW and BW (heel off)'s ankle joint angle increased in the terminal stance as the flexion of BW (heel off)'s ankle drastically increased. In the preswing, the ankle was more dorsiflexed during BW (heel off), and in the initial swing at 2.1°, it was less plantarflexed during BW (heel off). The total range of motion (A5, P<.001) also significantly different.

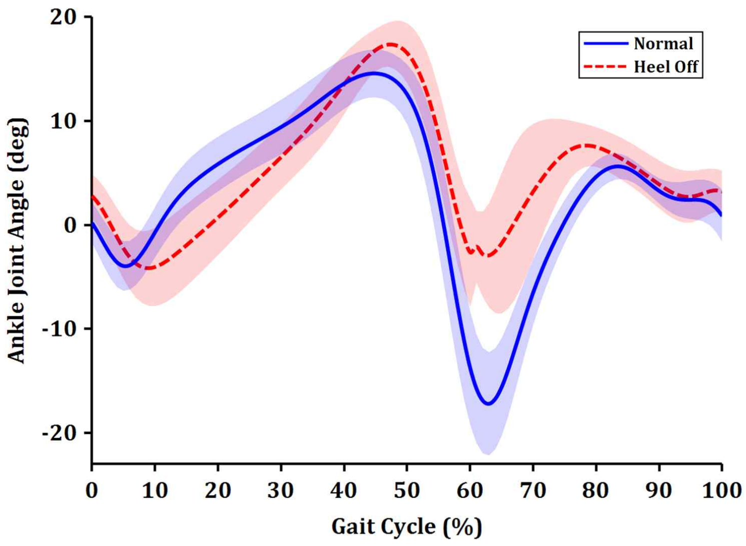


Figure 3.1. Ankle joint angles; FW vs. BW (heel off)

3.2.2 Knee joint angles

No significant differences in the knee position during FW and BW (heel off) was recorded throughout the stance phases of the gait cycle (K1-K2, P<.001; Figure 3.2). The parameter K3 was excluded because the knee is monotonically flexed during terminal stance [10]. The knee was less flexed at toe off and initial swing (K4, P<.001) during BW (heel off) than during FW. The total range of motion of the knee was greater for FW (K5, P<.001).

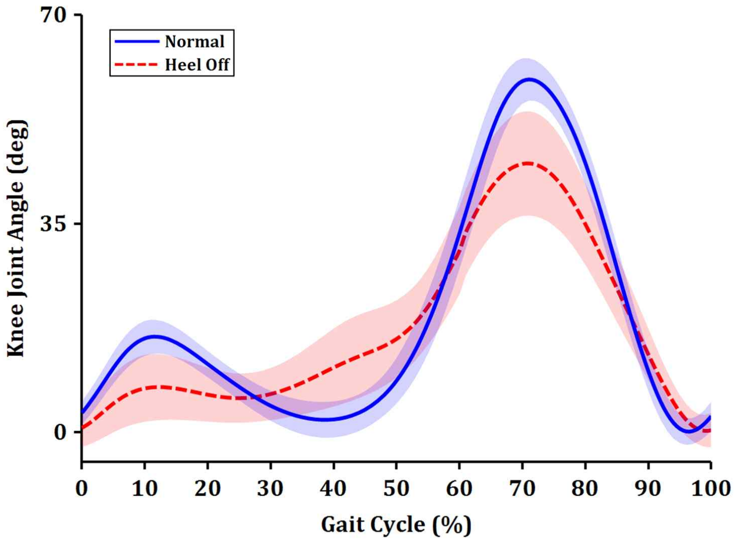


Figure 3.2. Knee joint angles; FW vs. BW (heel off)

3.2.3 Hip joint angles

The hip position during FW and BW (heel off) significantly differed throughout the whole gait cycle (H1-H2, P<.001; Figure 3.3). The hip was less flexed at initial contact during FW, and less flexed at toe off during BW (heel off), and less extended at preswing during BW (heel off). The total range of motion (H3, P<.001) did not significantly differ between FW and BW (heel off).

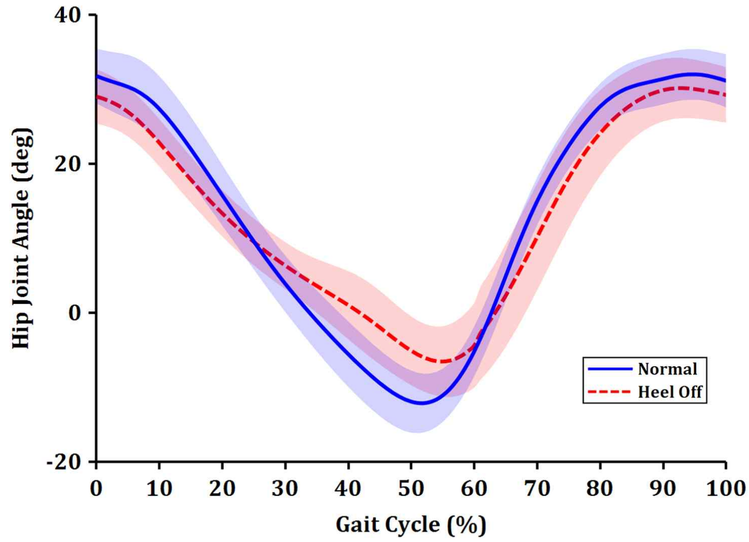


Figure 3.3. Hip joint angles; FW vs. BW (heel off)

3.3 Kinetics

3.3.1 Joint moments

The maximum plantarflexion moment of the ankle joint at loading response phase during FW and BW (heel off) had no difference (AM1, P=.056; Figure 3.4). However, the maximum dorsiflexion moment during the stance phase showed significant difference (AM2, P<.001). During terminal stance, which is a period of heel rise, peak plantarflexor moments for FW and BW (heel off) significantly differed. The time-wise location of the peak plantarflexor torques, which is at the 50% of the gait cycle, was similar for FW and BW (heel off).

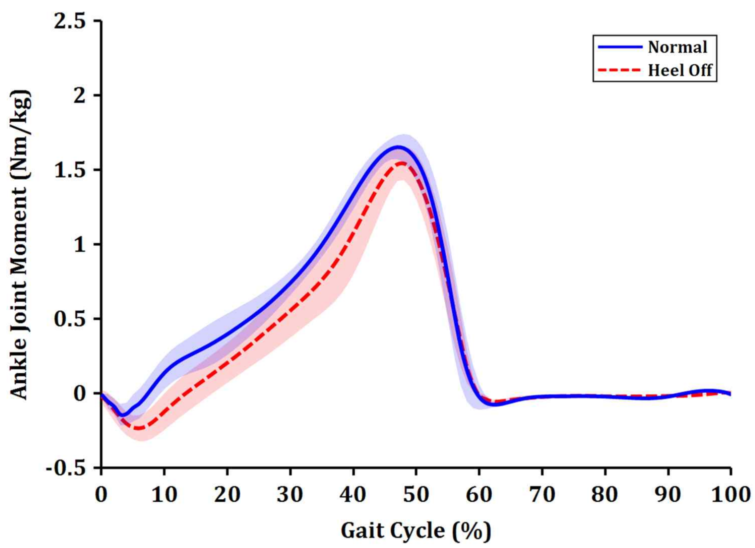
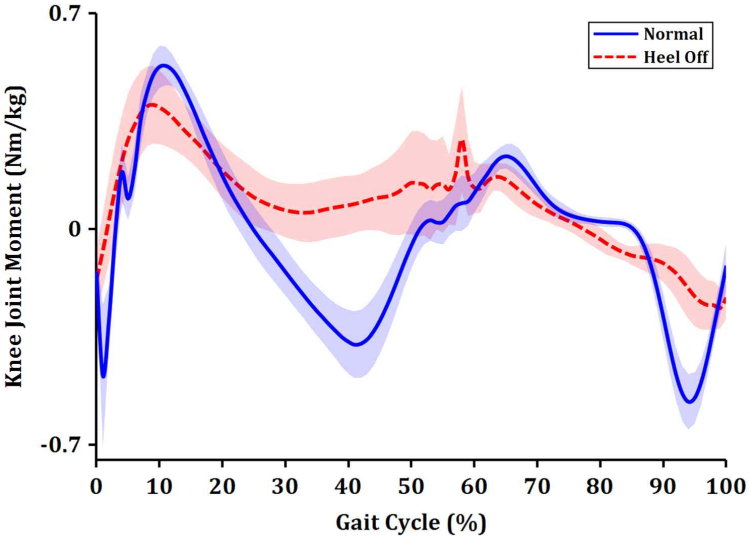


Figure 3.4. Ankle joint moments; FW vs. BW (heel off)

At the knee and hip joint (Figure 3.5), the apparent difference between peak moments of BW and FW showed during the midstance of the knee and the preswing of the hip.



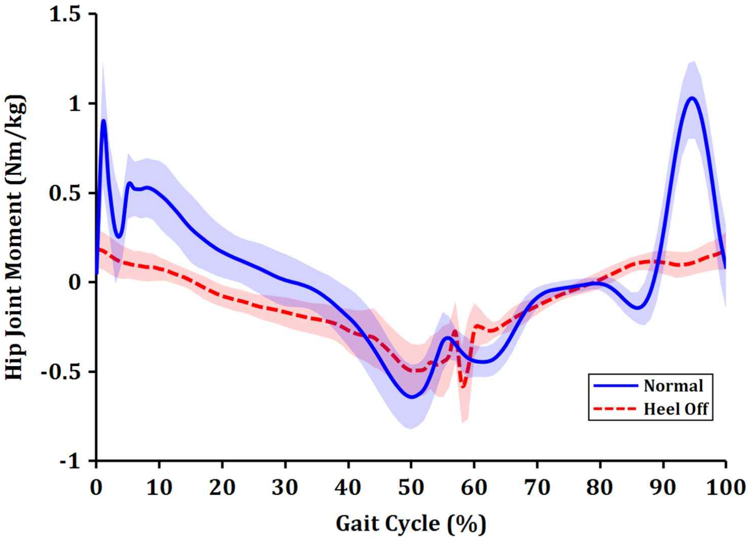


Figure 3.5. Knee and hip joint moments; FW vs. BW (heel off)

Table 3.2 Comparison of joint angles and moments variables; FW vs. BW (heel off)

Ankle Variable		Forward			Backward (heel off)			P
		Avg.	±	S.D.	Avg.	±	S.D.	
A1	Flexion at heel strike	0.2	±	2.0	3.3	±	2.1	<.05*
A2	Max. plantarflexion at loading response	-4.0	±	2.4	2.1	±	2.3	<.05*
A3	Max. dorsiflexion in stance phase	14.8	±	2.3	17.9	±	2.0	<.05*
A4	Max. plantarflexion in swing phase	-17.7	±	4.8	3.0	±	3.4	<.05*
A5	Total range of motion	32.5	±	4.0	21.4	±	3.3	<.05*
AM1	Max. plantarflexion moment	-0.2	±	0.1	-0.2	±	0.1	>.05
AM2	Max. dorsiflexion moment	1.7	±	0.1	1.6	±	0.1	<.05*
AP1	Max. power generation	4.4	±	0.4	1.2	±	0.2	<.05*
AP2	Max. power absorption	0.9	±	0.2	-2.9	±	0.6	<.05*

Knee Variable		Forward			Backward (Heel off)			P
		Avg.	±	S.D.	Avg.	±	S.D.	
K1	Flexion at heel strike	3.3	±	2.0	0.2	±	2.7	<.05*
K2	Max. flexion at loading response	16.2	±	2.8	36.8	±	7.1	<.05*
K4	Max. flexion in swing phase	59.6	±	3.3	45.7	±	8.4	<.05*
K5	Total range of motion	61.4	±	3.6	47.9	±	8.6	<.05*

Hip Variable		Forward			Backward (Heel off)			P
		Avg.	±	S.D.	Avg.	±	S.D.	
H1	Flexion at heel strike	31.8	±	3.7	29.5	±	3.8	<.05*
H2	Max. extension in stance phase	-12.3	±	3.9	-6.8	±	4.8	<.05*
H3	Total range of motion	45.2	±	2.8	37.7	±	4.3	<.05*

3.3.2 Joint powers

The joint power shows in Figure 3.6-8. During BW (heel off), the ankle decelerated during loading response to absorb the initial contact shock in the ankle joint. The plantarflexor muscle, gastrocnemius and soleus, activated to make ankle dorsiflexion slower and power absorbed. In midstance phase, the ankle joint plantarflexed to move the trunk backwards and it was the biggest power generation during BW (heel off) (Figure 3.6).

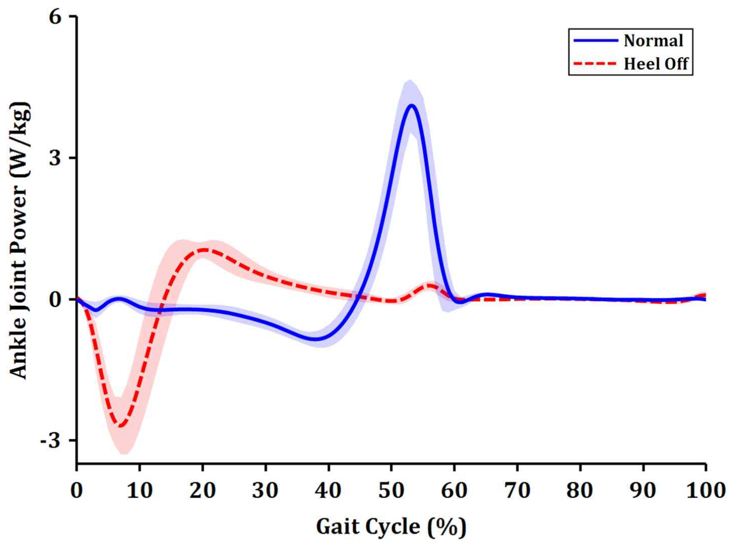


Figure 3.6. Ankle joint powers; FW vs. BW (heel off)

The knee joint extended in preswing phase and flexed in initial swing phase to propulse the foot backwards and to clear the foot on the ground, and the joint power was generated (Figure 3.7).

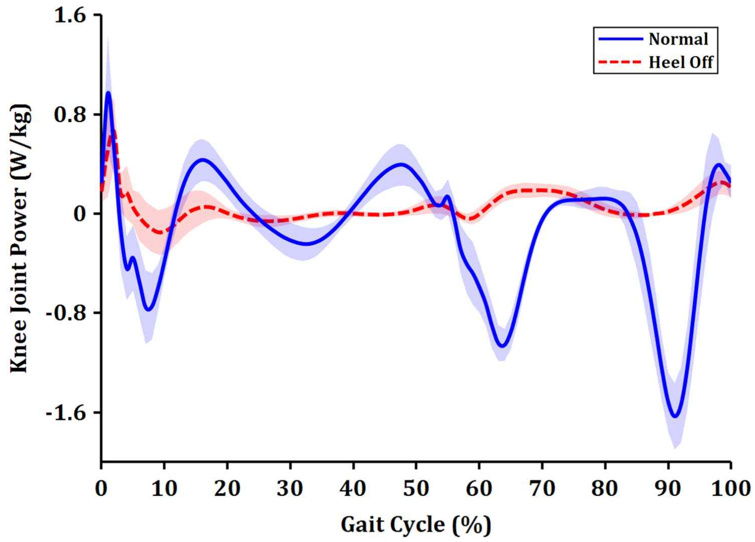


Figure 3.7. Knee joint powers; FW vs. BW (heel off)

The hip joint flexed and the largest power generated after the loading response phase. In terminal stance, the joint power absorbed to maintain the trunk vertically during walking backwards (Figure 3.8).

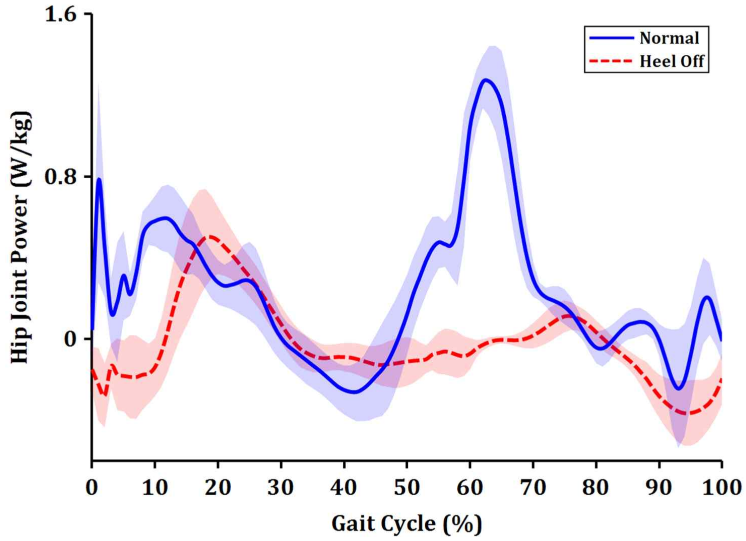


Figure 3.8. Hip joint powers; FW vs. BW (heel off)

3.3.3 Ground reaction forces

The GRF was rapidly raised due to support the whole body weight in loading response (Figure 3.9). The knee was flexed during mid-stance, the force plate briefly unloaded and the GRF drops below the body weight [14]. The second peak of GRF was smaller than first peak of GRF, since the knee and hip joints were just lifted the limb and moved backwards. Thus, the plateau shape which is not able to be seen in FW was observed during preswing phase.

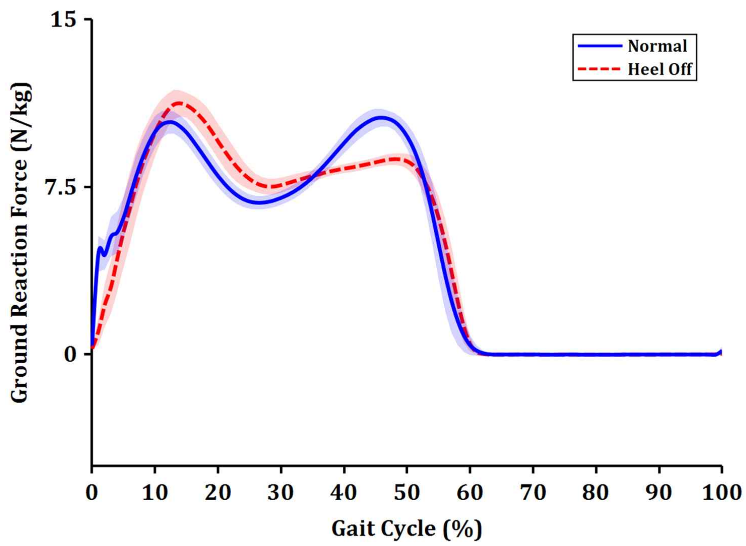


Figure 3.9. Ground reaction forces; FW vs. BW (heel off)

3.4 Electromyography

The average EMG pattern for each of the eight muscles are shown in Figure 3.10. The soleus had approximately the same peak values for both FW and BW (heel off). The tibialis anterior, vastus lateralis, and biceps femoris showed a distinct increase in their peak activation during BW (heel off). Only the gastrocnemius had a marked increase of the peak activation during FW.

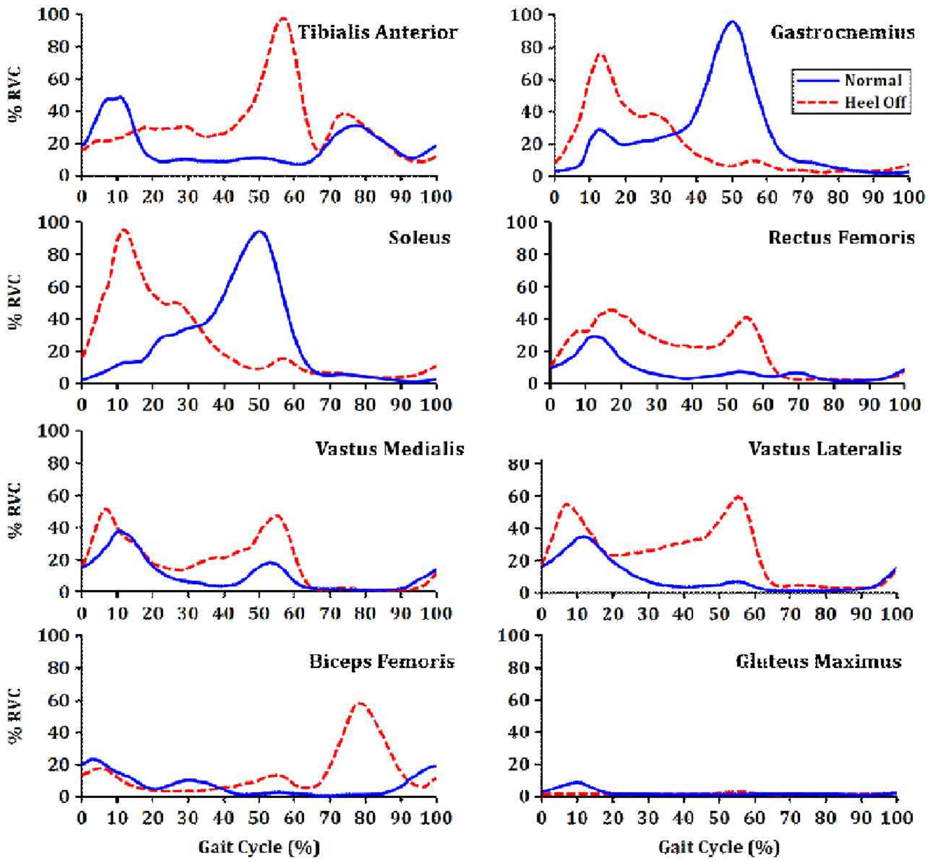


Figure 3.10. FW vs. BW (heel off)

The timing of activation of almost muscles changed for the two walking conditions, except in the cases of the rectus femoris, vastus medialis, and vastus lateralis. The changes for these muscles seems to be merely one of amplitudes. These three muscles were activated during the whole stance phase in BW (heel off). The gluteus maximus was not activated during BW (heel off).

4. Discussion

The walking speed was faster during FW than during BW, because the range over which the participant sensed safety and comfort was wider for FW. In other words, BW had a invisible direction of progress. Moreover, FW and BW displayed large differences, especially in walking speed, cadence and stride time, slower speed could disturb the rhythm of gait [18]. However, unlike the result of this study that showed differences in cadence and stride length, previous researches recognized the difference of average speed between FW and BW as slight [8, 10]. The stride length showed a significant difference, because in the hip joint, the average range of motion between flexion and extension had a great difference; flexion angle was 90 degrees, and extension angle was 20 degrees [19].

Figure 3.1, 3.2, and 3.3 present mean joint angles at the ankle, knee, and hip joint in one gait cycle. The overall amplitude of the angular displacement during FW and BW (heel off) had significant differences in the ankle and knee joint. The time-reversed angular pattern during BW (heel off) that resulted from our study corresponded to FW's data from existing studies [8-10] despite significant difference in the number of subjects. There were some differences; the hip joint was more flexed during BW (heel off) and the ankle joint during BW (heel off) was generally dorsiflexed in whole gait cycle than during FW.

Previous studies that used EMG to compare FW to BW (heel off) drastically differed on their muscle activity patterns [8-10]. The period of muscle activity was completely shifted due to the reversed direction of movement [9].

At the hip joint the angular movements were almost identical in FW and BW (heel off). In the loading response the hip joint was flexed and hip joint power was generated in BW (heel off). In the terminal stance, flexor moment was converted to extensor moment to maintain the trunk vertically during BW (heel off). The biceps femoris, knee flexor and hip extensor muscle, was activated in swing phase from hip flexion to extension in BW (heel off). This muscle could act to brake knee extension during late swing phase. It also assist the braking hip flexion and initiating hip extension in BW (heel off). The gluteus maximus, was activated at the loading response phase in FW, but in BW (heel off) the activity was much lower amplitude. The one of the previous studies showed same results in this muscle. The rectus femoris, hip flexor and knee extensor, was markedly changed in BW (heel off). This muscle was active in whole stance phase as compared to activity at loading response phase and toe-off in FW. This muscle generated the flexor moment before and after the initial contact.

The knee joint was not similar in angular pattern, especially stance phase. In initial contact the knee was flexed, and from initial contact to mid stance the knee was continuously extended in BW (heel off). The knee slightly flexed in terminal stance to drop the body weight for opposite foot contact and ready to propel the body backwards. The knee extensor muscles, vastus lateralis, vastus medialis, and rectus femoris, showed a massive activation throughout the whole stance phase, particularly preswing. Thus, during this period there was simultaneous knee extension.

The ankle joint during BW (heel off) was more dorsiflexed than during FW. In loading response, the ankle plantarflexor muscles, gastrocnemius and soleus, were activated to decelerate the foot. At this period plantarflexion moment was generated. The power was absorbed at the ankle joint to absorb the shock of walking in BW (heel off). To move the body backwards, the ankle joint was plantarflexed in mid stance, and the largest power at the ankle joint was generated. The tibialis anterior, ankle dorsiflexor, was activated to assist the body propulsion backwards in preswing and power was generated slightly. In BW (heel off), the ankle was dorsiflexed again to clear the foot during swing phase.

The patterns of the vertical GRF curves also differed between FW and BW (heel off). The GRF on both groups exhibits two main peaks when body mass is accelerated upward during the double support phases of early and late stance and a trough during the single support phase of mid stance when the body accelerates downward. However, the two peaks are roughly symmetrical in FW, whereas in BW (heel off) the first peak caused by the loading of body weight is always greater than the second peak caused by the heel push off.

This study only studied the sagittal plane, therefore further research is needed to analyze the coronal plane. The trained backward walkers is needed.

5. Conclusion

The aim of the present paper was to analyze the mechanism of gait through acquiring data on the kinematic and kinetic patterns of BW and FW. We have assessed the difference in angular patterns between time-reversed BW (heel off) and FW, which was statistically significant. The kinetic analysis of gait, rarely studied in previous researches, is implemented in the current study. The moment patterns of time-reversed BW (heel off) and FW were also statistically significant. The data of EMG and joint powers is also used to analyze the muscle activation during BW (heel off), however, this showed great differences with previous studies.

Finally, following conclusions are worth pointing out this paper:

1. BW (heel off) is a invisible direction of progress and it causes the speed slower than FW. Slower speed could disturb the rhythm of gait, so the stride characteristics show significant differences.
2. The main propulsion and shock absorption joint during BW (heel off) is the ankle joint. It is generally dorsiflexed in whole gait cycle during BW (heel off) than during FW to absorb the shock.
3. Maintaining the stability in BW (heel off), the knee joint is more flexed than during FW. And the knee extensor muscle is activated twice.
4. The hip joint is more flexed during BW (heel off) and the hip extensor muscle is rarely activated.
5. The second peak of GRF during BW (heel off) is plateau than first peak of

GRF during FW, since the knee and hip joints are just lifted the limb and moved backwards.

6. The patterns of angular, moment, and power during BW (toe off) show similar. However, the electromyography patterns show quite different due to the relaxed leg moves backwards.

Successful results in current and future research in the kinetic and kinematic data of BW will establish a fundamental mechanism of BW.

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