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Effects of Water Exercise on the Foot Pressure Distribution of a Female Adult with Hemiplegia: A Biomechanical Case Study

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ABSTRACT

This case study was conducted to determine the effects of water exercise on the foot pressure distribution (FPD) of persons who have a hemiplegia. A 43-year old female with hemiplegia acquired at the age of 3 years was selected from a local disability program. A 12-week water exercise program (60 min. per session and twice a week) focusing on gait training was developed and implemented as the intervention of this study. A recent product of the Pedar-X (Novel, Germany) was used to measure the FPD of hemiplegic gait before and after the intervention. Variables considered in this study included the average pressure (AP), contact area (CA), maximum pressure (MP), ground reaction force (GRF), and center of pressure (COP). The data collected were analyzed via the descriptive statistics and qualitative analyses on the graphical presentations of the FPD. Results revealed that the AP and CA of the hemiplegic foot was considerably increased before and after the intervention. Similar results were also found in the MP and GRF. Additionally, the graphical route of the COP related to hemiplegic foot was changed in a positive way after the intervention. It can be concluded that water exercise may be beneficial to restore hemiplegic gait. Limitations related to measurement and generalizability are further discussed.

Keywords : Water exercise, Hemiplegia, Gait, Foot pressure distribution

I. Introduction

Hemiplegia is the total paralysis of the arm, leg, and trunk on the same side of the body (Babalola & Taiwo, 2011). It is a typical symptom resulting from cerebral palsy, stroke, illness, injury, and intermittently the misuse of medications. Although no data are available for the prevalence of persons with hemiplegia, many researchers have shown that approximately 70-80% of stroke survivors have hemiplegia (National Institute of Neurological Disorders and Stroke, 2011). Also, Sherrill (2004) pointed out that a considerable number of individuals with brain lesions (including cerebral palsy, spinal cord injury, traumatic brain injury, etc.) have certain degree of hemiplegia depending on the severity of disability.

People with hemiplegia often have asymmetrical gait patterns and balance problems leading to fewer opportunities to participate in physical activity. With the decreased levels of physical activity participation, an individual with hemiplegia may encounter loss of physical fitness (Chen, Ashtonmiller, Alexander, & Schultz, 1991; Harada, Chiu, & Stewart, 1999; Mayo et al., 1999), metabolic decline (Ivey, Hafer-Macko, & Macko, 2008), and lack of motor skills (Kawahira et al., 2010), as well as difficulty in performing activities of daily living (Koc & Kilic, 2013). In addition, people with hemiplegia often tend to have problems associated with psychosocial variables such as depression, self-confidence, and social skills, which all together eventually impact the quality of life.

Perhaps one of the most significant problems in persons with hemiplegia would be difficulty in walking caused by an asymmetrical gait pattern. Generally, hemiplegic gait can be characterized as tendances to occur with any disorder producing an immobile hip or knee, leaning to the affected side with the arm on that side holding in a rigid and semi-flexed position (Sherrill, 2004). Such the gait pattern lead to deficit in mobility and motor capacity which in turn increases the risk of the secondary condition (e.g., severe injuries as a result of fall).

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Conversely, exercise can be an effective means of restoring abnormal gait patterns in persons with hemiplegia. Researchers have shown that exercise has positive impact on hemiplegic gait and lower limb (Babalola & Taiwo, 2011; Gharib, El-Masksoud, & Rezk-Allah, 2011; Kawahira, Shimodozono, Ogata, & Tanaka, 2004; Yosuke et al., 2010), upper extremity functioning (Kawahira et al., 2010; Park et al., 2012), posture (Baek, Kim, Kim, Oh, & Yoo, 2009; Gray, Juren, Ivanova, & Garland, 2012), functional skills for ADLs (Koc & Kilic, 2013), and balance (Olawale & Ogunmakin, 2006). Also, evidence shows that participation in an adapted physical activity program can induce decreasing the degree of depression, as well as improving mobility functioning (Macko et al., 2008).

Water exercise is well known as an effective way to restore the function of both upper and lower limb in persons with disabilities. Water provides a controllable environment for reeducation of weak muscles and skill development because movement in water is not only easier but less painful (Koury, 1996). Researchers also suggest that persons with orthopedic disabilities can benefit in aerobic capacity (Heberlein, Perez, Wygand, & Connors, 1989; Vickery, Cureton, & Langstaff, 1983), muscular strength and endurance (Ruoti, 1989). The psychological benefits of water exercise has also been well documented in literature (Grove & Gordon, 1992; Howley & Franks, 1986).

Recently in Korea, a considerable number of research studies have been conducted to investigate the effects of water exercise on persons with hemiplegia. Summarizing the results of these previous studies, water exercise has positive impact on physical fitness and the range of motion in lower limb (Lee & Kang, 2009), peripheral circulation function and autonomic nervous system (Cho et al., 2009), blood lipid (Nam, Lee, Cho, & Kim, 2007), and motor skills (Chang, Yoo, & Jeong, 2009).

Given the these benefits, some researchers have also been interested in how water exercise affects the hemiplegic gait. Jin and Jeon (2012) conducted a study to evaluate changes in hemiplegic gait and the muscular strength of lower limb after participating in a 12-week aquatic lower limb muscle strengthening program. Results revealed that along with positive changes in muscular strength, gait distance and time was significantly increased; whereas, gait course angle was significantly decreased. Additionally, two studies were conducted to compare the effects of water exercise and land-based exercise on hemiplegic gait (Lee & Kang, 2010; Lee & Kim, 2008). According to the results of these two studies, positive changes in both groups were found; however, differences between two groups were not statistically significant. Therefore, it was concluded that water exercise could be as much beneficial as land-based exercise for the gait of persons with hemiplegia.

One limitation in the previous gait studies related to water exercise and hemiplegic gait is measurement. Measurement used in these studies are mostly field-based tests such as 3 m/6 m/12 m walk, walking stairs up and down, maximal walking velocity test, walking endurance test, gait velocity and time using a force plate. Although these tests are known as valid, they provide indirect information related to hemiplegic gait. For better understanding of abnormal walking in persons with hemiplegia, one needs more direct and empirical evidence that explains biomechanical mechanism associated with the hemiplegic gait patterns. In addition, the inter- and intra-individual differences of hemiplegic gait are great; thus, a case study seems appropriate.

The analysis of foot pressure distribution (FPD) has been recently and widely used to determine the characteristics of gait more systematically and scientifically (Lee, Yang, Lee, & Park, 2009). This mainly provides information on foot pressure, ground reaction force, contact area, center of pressure, and velocity that may be critical to assess hemiplegica gait. However, no research using the FPD analysis has been found. Therefore, the purpose of this case study was to determine the effects of water exercise on the hemiplegic gait of a female adult with hemiplegia.

II. Methods

1. Research design and participants

The present study was a single-subject case study with a pre-post test design. In this case, the participant was assessed before and after intervention that was a 12-week water exercise program.

Based on two selection criteria (hemiplegia and independent walking), a female adult with hemiplegia participated in this study. She was 43 years old and had a acquired hemiplegia at the age of 3 years, as a result of the misuse of a medication. Using the Modified Ashworth Scale (MAS), her spasticity was graded as "G1+" which corresponds to a slight increase in muscle tone, manifested by a catch, followed by minimal resistance throughout the remainder (less than half) of the range of motion (Bohannon & Smith, 1987). She was selected from a local disability sport program located in Changwon city, Kyongnam province, Korea.

The height and weight of the participant were 160 cm and 53 kg, respectively. She had been paralyzed in her left side of the body and was diagnosed as the third degree of brain lesion at the age of 3 years. Her hemiplegic gait pattern was unique showing the steps with the right leg was short and fast, as supporting the affected left leg. This move made her upper body lean forward with hips pulled out and easy to fall. Regarding the severity of disability, she had difficulty to walk on uneven floor, slope, and stairs which in turn, significantly affected daily locomotion. According to her med-

Table 1. The descriptions of water exercise

	Duration (min)	Activity	Descriptions
Warm-up	5	Stretching on land	- Stretching for head, shoulder, chest, waist, knees, ankles, and hands
Main exercise 1	20	Flutter kick while sitting on the deck	- Flutter kick while sitting on the deck, supported by both arms behind
		Flutter kick while holding the kickboard	- Flutter kick in the water while holding the kickboard, with support
Main Exercise 2	30	Training to strengthen the affected leg	- Unilateral squats with body weight supported only by the affected leg - Stationary lunge and forward lunge with using the affected leg as the leading limb - Jumping with the affected leg
		Gait Training	- Forward walking emphasizing the heel-to-toe motion - Backward walking emphasizing the toe-to-heel motion - Toe walking then heel walking while keeping the balance of upper body
Cool-down	5	Stretching in the water	- Hip extensors/flexors, knee extensors/flexors, posterior/anterior lower leg

ical history, she had a surgery to cut femoral nerves in quadriceps and to attach them to knee extensor muscles for better walking. Despite the hemiplegic gait, she had no intellectual disability, nor other secondary conditions.

2. Intervention

An individualized water exercise program was developed for the participant based on the literature related to aquatic therapy programming for orthopedic rehabilitation (Grosse, 2001; Koury, 1996; Lee & Kim, 2008). This program was held twice a week for 16 weeks. The duration of each session was 60 minutes. The elements of program were fixed for the whole sessions, but the intensity of exercise was gradually increased. The details of the program is described in <Table 1>.

The program consisted of warm-up, main exercise, and cool-down. The main focus of the warm-up and cool-down session was muscle relaxation mainly using stretching. The main exercise was divided into two sub-sessions. In the first session, the participant was instructed to kick using both feet; whereas, strengthening the affected leg and walking in water was the main goal of the second session.

The intensity of exercise was assessed by ratings of perceived exertion (RPE) and target heart rate (THR). The RPE was monitored by simply asking the participant how hard the given exercise was in the middle of the main exercise. On the other hand, the THR was monitored by checking the number of pulses on the carotid artery (neck) after the main exercise. For the first 8 weeks, the activities were provided with the 7-13 level of RPE; whereas, the 9-15 level of RPE was applied for the next 8 weeks (Lee & Kim, 2008). In addition, THR was determined by the percentage of HRmax. This method has been recommended for the relatively less fit ones such as the elderly or persons with disabilities (American College of Sports Medicine [ACSM], 2010). For the first 8 weeks, 50-60% of HRmax was applied; whereas, 70-80% was required for the next 8 weeks.

3. Measures

The Pedar-X (Novel, Germany), a dynamic pressure distribution measuring system, was used to analyze the foot pressure distribution of the participant. This system has been known as a valid and reliable pressure distribution measuring system for monitoring local loads between the foot and the shoe (Park, 2009; Park & Cho, 2008). This measuring system was tethered to a notebook via a fiber optic USB cable using a built-in Bluetooth TM telemetry which made the system mobile and flexible to collect the walking parameters of the participants. In addition, a pair of soft running shoes made by N company was used in this study. The elements of measuring tools are shown in <Figure 1>.

Upon receiving the approval of institutional review board (IRB), the investigators contacted the participant and received the voluntary participation from her. On the day of the first experiment, the participant was instructed for the procedure. Prior to the actual experiment, a warm-up session with a light stretching and walking was given to the participant. For the experiment, the participant wore a belt attached with the Pedar-X box which was controlled by the Microsoft Bluetooth software. She also wore the experimental shoes in which the measuring insoles were inserted. To maintain the walking speed, a metronome was set up at 60 bpm. During the experimental walking, the Bluetooth module transferred the data via wireless communication with the computer. The task of 10 step walking was given to the participant, and on the 5-6th step the data were transferred and saved in the computer. The measuring variables

Figure 1. The front and rear view of the participant wearing the Pedar-X

of this study included average pressure(AP), maximum pressure (MP), ground reaction force (GRF), contact area (CA), and the center of pressure (COP) while walking. These variables have been considered as the critical elements of foot plantar pressure because these are directly related to one's gait pattern (Lee, et al., 2009; Park, 2009; Park & Cho, 2008; Yoon, Lee, S. Y., & Lee, H. M., 2009).

4. Data Analyses

The data collected were encoded into the SPSS Windows 20.0 statistical software for further analyses. Descriptive statistics were used to determine the effects of water exercise after the intervention. The intra-individual differences were evaluated using the percentage of changes in each variables. In addition, The qualitative analyses for the graphical distributions of the COP were used to explain how the center of foot pressure was changed while walking. Ten regions of the plantar surface were identified for the analyses of the COP in this study (refer to figure 2).

III. Results

1. AP and CA

<Table 2> shows the results of AP before and after the intervention. The AP of the left (affected) foot for the participant was increased from 67.8 to 91.5 kPa resulting in

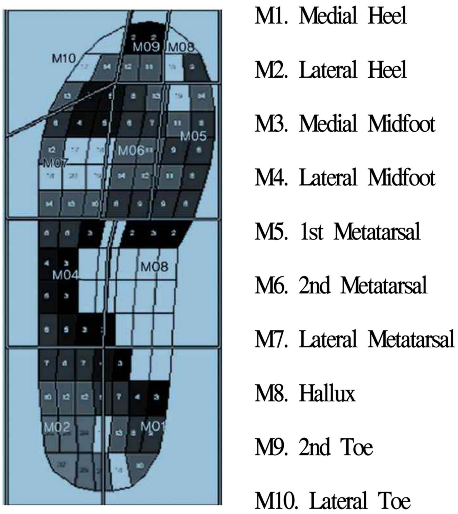

Figure 2. The regions of plantar surface

Table 2. Results of average pressure (unit: kPa)

Side of Foot	AP		Difference	% of Change
	Pre	Post		
Left (affected)	67.8	91.5	23.7	35
Right	85.7	104.6	18.9	22

Table 3. Results of contact area (unit: cm^2)

Side of Foot	CA		Difference	% of Change
	Pre	Post		
Left (affected)	87.4	114.2	26.8	31
Right	99.9	125.3	25.4	25

35% of change; whereas, the increased rate of the right foot was 22%.

The results of the CA were described in <Table 3>. The CA of the left (affected) foot in the post-test was 31% wider than that in the pre-test; whereas, the increase rate of the right foot was 25%.

2. MP and GRF

The more obvious evidence was found for the MP and GRF (refer to Table 4 and Figure 3, 4). The MP of the left (affected) foot was increased from 160.0 to 407.5 kPa with the increased rate of 154.7%; whereas, only 2.1% was increased for the right foot.

<Table 5> (also refer to Figure 3, 4) presents the results of the GRF before and after the intervention. The GRF of the left (affected) foot for the participant was increased from 338.9 to 561.3 N resulting in 66% of change; whereas, the increased rate of the right foot was 50%.

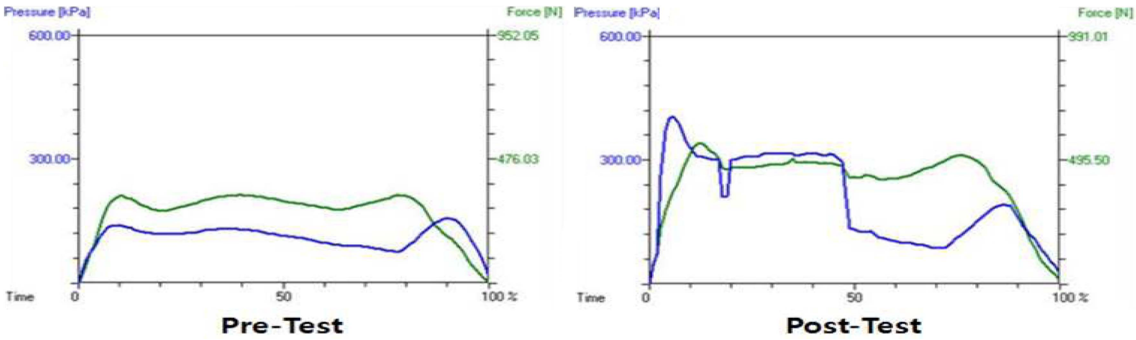

Figure 3. Changes in FPD and GRF for the affected (left) foot (one step)

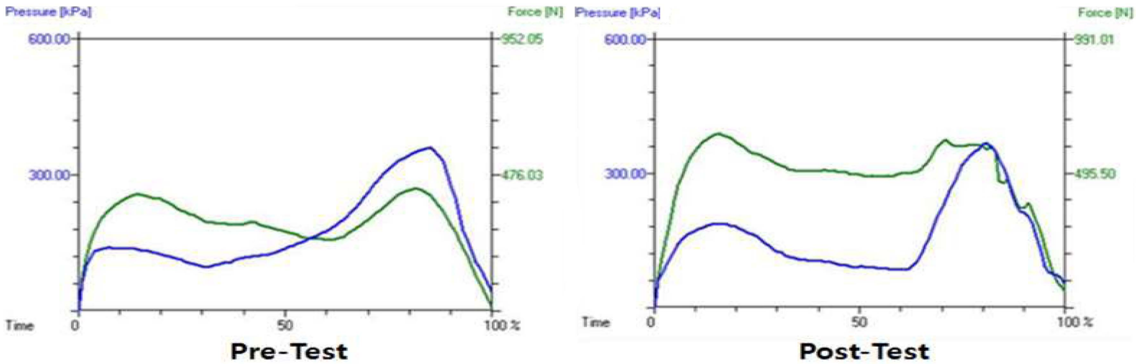

Figure 4. Changes in FPD and GRF for the right foot (one step)

Table 4. Results of maximum pressure (unit: kPa)

Side of Foot	MP		Difference	% of Change
	Pre	Post		
Left (affected)	160.0	407.5	247.5	154.7
Right	360.0	367.5	7.5	2.1

Table 5. Results of ground reaction force (unit: N)

Side of Foot	GRF		Difference	% of Change
	Pre	Post		
Left (affected)	338.9	561.3	222.4	66
Right	427.9	643.1	215.2	50

3. The Center of Pressure

Two segments of analyses were reported for the COP: (a) foot pressure distribution and (b) pathway of the COP. <Figure 5> presents the overall distributions of foot pressure before and after water exercise. The plantar pressure was determined by the color of the graphical presentation in which red, pink, and yellow were relatively greater than green, blue, and black in the degree of pressure. In the pictures of pre-test, the COP of the affected (left) foot was found in the M6 (2nd metatarsal) with the color of yellow; whereas, that of the right foot was located in M5 (1st metatarsal) with the color of red and pink. Also, the contact area of the affected foot was much smaller than that of right foot.

According to the pictures of the post-test, the plantar pressure of the affected foot was changed dramatically compared to that of the pre-test. The COP was shifted to M2 area (lateral heel) with the color of pink; whereas, not much change was found for the right foot after water exercise. Results also revealed that the contact area of both feet was wider. In addition, the color of black representing the area with the lowest pressure was greatly reduced in both feet.

<Figure 6> demonstrates the pathway of the COP before and after the intervention. In the pre-test, the COP of the affected foot had relatively a shorter than that of the right foot. Results also indicated that the COP of the affected foot was moved through M3 (medial midfoot); whereas, that of the right foot was shifted from M3 to M5 (1st metatarsal).

In the post-test, the COP pathway of the affected foot became considerably long and wider, as compared to that in the pre-test. However, the COP pathway of the right foot after water exercise showed a different shape, as compared to that in the pre-test. Two pathways in one step were simultaneously found for the right foot in the post-test. One pattern of the COP pathways was M3-M5, and the other pattern was M3-M4-M5. Nevertheless, the location of the

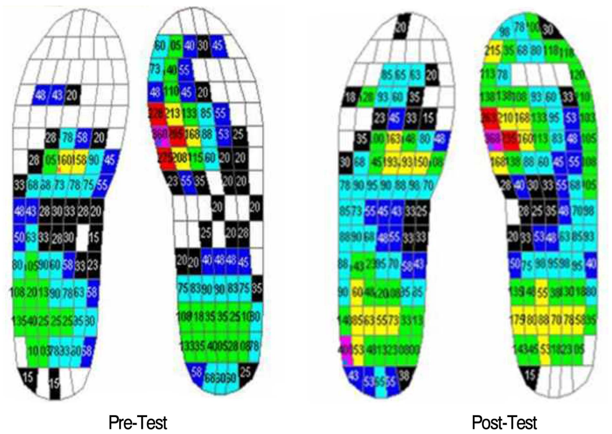

Figure 5. The graphical presentations of the FPD (one step)

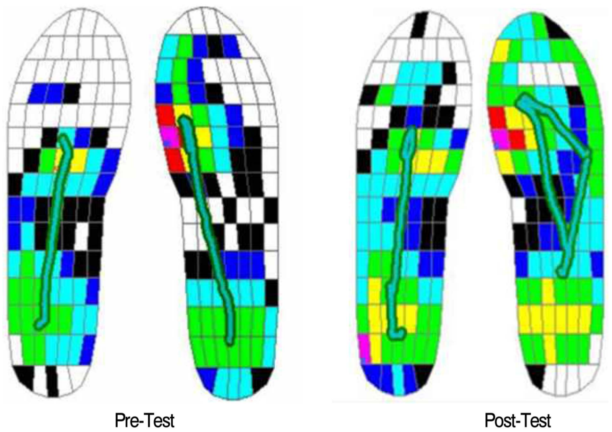

Figure 6. The pathways of the COP (one step)

COP pathway of the right foot was shifted to the middle after water exercise.

IV. Discussion

This study was conducted to determine the potential benefits of water exercise as a means of rehabilitation for hemiplegic gait. In spite of limitation in a case study, the investigators obtained several meaningful findings from the analyses of foot pressure distribution in this study.

The clearest evidence for the benefits of water exercise in this is the positive change of the AP and CA. In this study, results revealed that the AP and CA of the affected foot was increased up to 35% and 31%, respectively after the intervention. These results are in line with the findings of the previous studies regarding the effects of gait training (Babalola & Taiwo, 2011, Gharib et al., 2011; Kawahira et al., 2004) and complex exercise (Kim, E. J., Jung, Kim, T. H., & Bae, 2009; Lee et al., 2009) on the foot pressure distribution in persons with and without hemiplegia. The increase of the AP in this study seems due directly to the wider CA. These results reflect that the affected foot could produce more force than before. Also, these reflect that the time taken for a step with the affected foot became longer, which in turn, produced a mare stable gait pattern. Lee et al. (2009) also suggests that the FPD is strongly associated with the CA of the affected foot in persons with hemiplegia.

For better understanding of the AP and CA results in this study, it is necessary to explain hydrodynamics and its impact on muscular strength and endurance. In water, buoyancy acts as a counterforce to gravity, providing support for the body and resisting downward movement (Koury, 1996). Also, water drag acting on the body is another source of resistance. For these reasons, the water exercise of this study could provide the participant with an appropriate condition for resistance training. Especially, the muscle groups associated with the affected foot seem to be more benefited from participation in water exercise. A considerable number of research studies have shown consistent results that water exercise improves the muscular strength and endurance of the lower extremities; thus, has positive impact on the hemiplegic gait (Jin & Jeon, 2012; Lee & Kang, 2009; Lee & Kim, 2008).

An interesting result was found in the MP of the affected foot. In the pre-test of the study, the MP of the affected foot was relatively lower than that of the opposite (right) foot (160 vs. 360 kPa); however, after water exercise, it turned out a reverse result (407.5 vs. 367.5 kPa). These results may represent the transferring process of force from the right to left (affected) foot while walking. These results may be due primarily to training for body alignment and posture in water. In this study, a lot of hands-on drills were implemented to correct the proper alignment and posture of body parts during the gait training in water. Therefore, it is believed that water exercise can improve the participant's alignment and posture that are a critical element for better balance (Koury, 1996; Olawale & Ogunmakin, 2006).

Another remarkable finding in this study is the margin of change in the MP provided with the increased rate of 154.7%. A possible reason for this is the high intensity of force produced by the affected foot when contacting the ground. This can be explained by the graphical changes in <Figure 3>. The highest peak of the MP curve was produced when the heel contacted the ground, and from that point to the midfoot, the curve was relatively higher than metatarsal and toe area. Therefore, it can be assumed that the smaller area with shorter time when stepping would produce a great deal of the MP. Research also shows evidence to support the relationship between the high intensity of force and the FPD (Lee et al., 2009).

Similar results were found in the GRF of the affected foot showing the increased rate of 66% in this study. These results are partially supported by previous findings (Kim et al., 2009). It can be assumed that the increase of the GRP of the affected foot is resulted from the increase of the MP and AP. Many researchers also suggest that the GRF is strongly associated with the MP and AP (Kim et al., 2009; Yoon et al., 2009).

One of the most unique results in this study is the MP and GRF curve shown in the post-test of <Figure 3>. When the heel of the affected foot contacted the ground, the highest peak of the MP was produced, as followed by the highest peak of the GRF. However, when taking off, the second highest peak of the GRF was proceeded by that of the MP. In general, the GRF is produced as a function of the FPD (Olsson, 1990); but not in this case. This may represent the unique feature of hemiplegic gait in the process of rehabilitation. However, more empirical studies should be needed to explain the kinetic and kinematic mechanism associated with the starting order of the FPD and GRF when the affected foot is taking off.

The COP is the point location of the vertical ground reaction force vector (Winter, 1995). It represents a weighted average of all the pressures over the surface of the area in contact with the ground. In normal gait, plantarflexor activity is associated with the anterior move of the COP; whereas, invertor activity is related to its lateral move. In this study, the COP of the affected foot was absent in the pre-test, but it was found in lateral heel after water exercise (refer to Figure 5). This suggests that the balance of the lower extremities is improved because the COP is closely associated with the balance (Benda, Riley, & Krebs, 1994). Meanwhile, Figure 6 in this study presents the changes in the pathways of the COP. When comparing the pre- and post-test for the affected foot, the pathway of the COP became somewhat longer and thicker after water exercise. This may be due to the plantarflexion components of water activities which is critical for the sound transfer of the COP in normal walking.

Another striking finding in this study is the change in the COP pathway of the unaffected (right) foot after water exercise (refer to the post-test of Figure 6). Unlike the results of the pre-test, the pathway of the COP in the post-test became shorter and was divided into two making a triangle in shape. Two possible reasons may explain these results. First, this may be a natural process of adaptation. The participant was used to asymmetrical gait pattern leaning her body to the right side, and with water exercise, she started shifting force to the affected side. For this reason, the neuromuscular activities associated with the COP of the unaffected foot may not function properly. However, this phenomenon is expected to occur temporarily as a compensate. The other reason that may explain the COP pathway of the unaffected foot is a measurement error. In the pre- and post-test of this study, the data were collected from one trial. Even though the investigators attempted to minimize the measurement errors associated with the Pedar-X experiment, the validity and reliability of this measurement cannot be fully guaranteed with one trial. Experts also suggest that when measuring the Pedar-X, many trials are needed to minimize errors and to enhance validity and reliability (Lee et al., 2009).

It should be noted here that this study had limitation that the kinematic variables were not considered. Variables such as trunk rotation, arm swing, hip rotation, knee rotation, and ankle motion are all important factors to affect gait (Chao & Cahalan, 1990). Without further information about kinematic variables, it may not be sure that water exercise is absolutely effective for restoring hemiplegic gait.

V. Conclusion

The purpose of this case study was to determine the potential benefits of water exercise related to rehabilitation for hemiplegic gait, and the investigators were able to find some evidences to prove these benefits. Summarizing the results of this study, the middle aged female participant with hemiplegia was able to considerably increase the average pressure, contact area, maximum pressure, ground reaction force, and center of pressure. Given these findings, it can be concluded that participation in a 12-week water exercise program may be helpful to restore hemiplegic gait.

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