Effects of Ankle Control Training Combined with NMES on Foot Function and Balance in a Healthy Adult: A Pilot Study

Yu-Sik Choi, PT, PhD[1], Soo-Yong Lee, PT, PhD[2], Kwang-Bin An, PT, PhD[3], Chang-Yoon Baek, PT, PhD[4], Woo-Nam Chang, PT, PhD[*5]

[1]*Dept. of Physical Therapy, Seoul Metropolitan Seonam Hospital, Republic of Korea*

[2]*Dept. of Physical Therapy, Severance Rehabilitation Hospital, Yonsei University, Republic of Korea*

[3]*Dept. of Physical Therapy, Bobath Memorial Hospital, Republic of Korea*

[4]*Dept. of Physical Therapy, National Health Insurance Ilsan Hospital, Republic of Korea*

[*5]*Dept. of Physical Therapy, College of Health & Welfare Science, Yong-In University, Republic of Korea*

Purpose This study was to investigate the effects of ankle control training combined with neuromuscular electrical stimulation (NMES) on foot function and balance in a healthy adult. ***Methods*** Eight healthy people were selected for the study. The intervention was applied the NMES on gastrocnemius (GCM) in upright standing. Ankle control training was combined with NMES. The intervention was performed for 30 minutes a day, 5 times a week, for four weeks. Ankle Range of Motion (ROM), Knee to Wall Test (KWT), Foot Pressure (FP), and Surface Electromyography (sEMG) were used to measure foot function. and Sway Index (SI) was used to measure balance. ***Results*** The intervention group showed a statistically significant increase in ankle ROM (p<.05) and KWT (p<.05). FP (p<.05) and sEMG (p<.05) show a statistically significant change. SI show a statistically significant decrease except when standing on a firm pad with eyes open. ***Conclusion*** Ankle control training combined with NMES was effective in foot function and balance.

Key Words Ankle, Balance, Foot, Gastrocnemius, Neuromuscular electrical stimulation

Corresponding author Woo-Nam Chang (wnchang@yongin.ac.kr)

Received date 20 January 2024
Revised date 02 February 2024
Accept date 12 February 2024

Ⅰ. Introduction

The ankle joint has a major impact on balance and posture control when humans stand and walk,[1)] and provides shock absorption to keep the trunk stable when walking.[2)] The ankle joint supports weight bearing through the contraction of the muscles of the lower extremity and maintains good posture by sensory input from the feet.[3)] Proprioception in the ankle joint is used to balance postural sway.[4)] Insufficient proprioception due to anatomical instability of the musculoskeletal system or muscle weakness can contribute to ankle joint instability.[5)] Factors of functional ankle instability include deficits in joint positioning sense, delayed calf muscle reaction time, decreased range of motion in dorsiflexion, and weakness of the ankle muscles.[6,7)]

The gastrocnemius (GCM) is a muscle in the lower extremity that, along with the soleus, forms the Achilles tendon, which helps stabilize the ankle and knee when standing and is involved in plantar flexion of the ankle.[8)] The GCM functions in propelling the lower extremity forward during walking by strongly flexing the knee and ankle joints.[9)] In an open kinetic chain, the GCM lifts the heel during plantar flexion of the ankle joint, functioning as a supinator at the subtalar joint, and flexes the knee joint in a closed kinetic chain.[10)] The soleus forms the medial side of the Achilles tendon, making medial inversion of the ankle, and is responsible for the stability and balance of the ankle in a standing position.[5)] The soleus and GCM generate approximately 93% of the ankle plantar flexion torque.[11)] Anatomical malalignment of the musculoskeletal system, muscle weakness, and insufficient

http:dx.doi.org/10.17817/2024.02.02.1111856

proprioception can lead to weakness of the GCM,[12] contributing to the functional instability of the ankle joint.[13] The ankle strategy shortens the soleus and GCM, which negatively affects joint alignment, stability, and balance.[14,15] Insufficient length of the soleus, GCM, and Achilles tendons and abnormal ankle joint structure limit the movement of the foot and prevent the tibia from moving forward in relation to the talus.[6] This will result in limited ankle joint range of motion, asymmetrical posture while walking, impaired balance, decreased walking function, and difficulty with fine motor control.[16]

A therapeutic approach to the restoration of joint alignment is training for proper movement through muscle stretching.[17] Eccentric muscle contraction training is an effective way to increase neuromuscular activity[18] and has the advantage of being less demanding on the cardiovascular system and requiring less energy than regular training.[19] Previous studies have reported that training to activate eccentric contraction of the plantar flexor had positive effects on a posterior shift of the center of foot pressure, balance, and walking in a standing position.[20,21] Such ankle control training has been widely applied to patients to maintain and increase ankle range of motion and enhance ankle stability.[22] In particular, heel raise up & down exercises not only strengthen the GCM, but also improve the alignment of lower extremity and circulation.[17]

Neuromuscular electrical stimulation (NMES) is a technique for activating muscles through electrical stimulation and is useful for strengthening and activating muscles.[23] There are two types of NMES: eccentric NMES, which directly stimulates the motor nerves to induce muscle contraction to produce the desired movement, and concentric NMES, which indirectly increases the physiological activity of the muscle by stimulating sensory receptors or sensory nerves.[24] Innervated muscles are caused by depolarising the highly excitable nerves first, while denervated muscles are caused by depolarising the muscle itself.[23] Electrical stimulation of denervated muscles is called electrical muscle stimulation, and electrical stimulation of innervated muscles are called NMES.[25]

This repetitive electrical stimulation and muscle contraction increase the activity of skeletal muscles and lead to biochemical, physiological, and structural changes.[10] There were many studies on changes in toe-off in the swing phase of the gait cycle by applying NMES to the tibialis anterior muscle in relation to walking.[26,27,28] Recently, various therapeutic approaches combining NMES, exercise therapy, and surface electromyography have been studied.[29,30]

Thus, this study aims to determine the effects of ankle control training with NMES on the GCM on foot function and balance in a single group of healthy adults. This was a preliminary study to design new therapeutic approaches by providing clinical evidence for NMES interventions in GCM.

II. Materials and Methods

1. Study subjects and period

The study was conducted on eight healthy volunteers, three men and five women, recruited from Yangcheon-gu, Seoul, South Korea. Subjects were fully informed of the purpose and timeline of the study and agreed to participate in the study. This study was conducted after obtaining approval from the Institutional Review Board (IRB) of Yong-In University (IRB Approval No: 2206-HSR-263-2).

The inclusion criteria were as follows: those who could walk independently, those without restricted ankle range of motion, and those who had no joint contractures, pain, or fractures in the musculoskeletal system.[31] The exclusion criteria were as follows: those with metal implants in their calves and ankles or those with a history of heart disease.[23] The character-

Table 1. General characteristics of the subject

Variables	Subject (n=8)
Gender (M/F, %)	3/5 (40/60)
Dominant side (R/L, %)	7/1 (87/13)
Age (year)	34.38±5.85[a]
Weight (kg)	61.88±6.27
Height (cm)	166.50±4.54

[a]Mean±standard deviation.

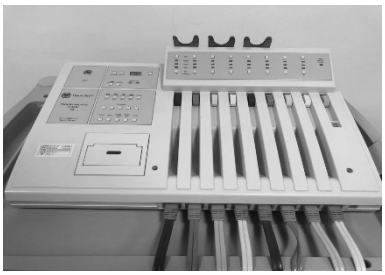


Figure 1. Neurotech

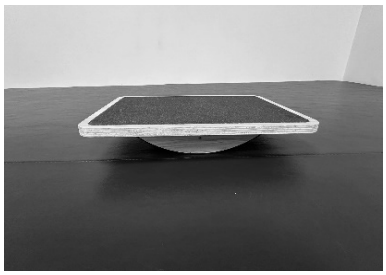


Figure 2. Rocker board

istics of the study subjects are as in Table 1. This study was conducted for four weeks from July 3 to July 28, 2023, at S Hospital in Yangcheon-gu, Seoul.

2. Procedure and Intervention Methods

The intervention program in this study was modified and supplemented by referring to the studies by Cheng et al. (2010)[30] and Choi & Chang (2022).[21] The therapy started with subjects in a standing position. An NMES device (Neurotech, Bio-Medical Research Ltd., Ireland) (Figure 1) was used for the exercise therapy intervention in the study group. This equipment is used to induce muscle contractions in the GCM. A rocker board (StrongTek Professional Wooden Rocker Board, Slantek, U.S.A) (Figure 2) was used for eccentric and concentric muscle contraction of the GCM. Measurements were performed at the same location.

1) Ankle control training

(1) In standby, stand in an upright position, adjust the base of support to the width of the pelvis, and maintain pelvic neutrality (Figure 3A).

(2) During the 5 seconds that the GCM is electrically stimulated, shift the foot pressure on the rocker board forward, causing the GCM muscle to concentrically contract so that the heel lifts off the ground. When shifting the center of gravity forward (heel off), the front plate of the rocker board was placed on the floor (Figure 3B).

(3) For 5 seconds without electrical stimulation to the GCM, stand on a rocker board with foot pressure posteriorly and eccentrically contract the GCM until the heel touches the ground. When shifting the center of gravity backward (forefoot lifted), the back plate of the rocker board was placed on the floor (Figure 3C).

3. Measures and Methods

1) Ankle range of motion test

The range of motion test, an assessment method with proven reliability and validity, was performed using a digital goniometer.[14] Normal ranges are 10° to 20° for

(A) Neutral position (B) GCM concentric contraction (C) GCM eccentric contraction

Figure 3. Ankle control training

Figure 4. Digital goniometer

(A) (B)

Figure 5. Knee to wall test

Ankle dorsiflexion and 40° to 50° for ankle planter flexion, and joint mobilization measurements were performed by referring to the international sagittal frontal transverse method (SFTR) for the axis, stationary arm, and moving arm. For manual dorsiflexion, the subject's heel was supported by the rater's palm. To increase the reliability of the test, the same rater conducted the test. Basic posture was measured using a digital goniometer in a supine position with the knees extended and the heels placed at the end of the examination table.[31] The angles were measured with the stationary arm parallel to the fibula and the moving arm parallel to a line connecting the lateral calcaneus to the 5th metatarsal head (Figure 4).[20]

2) Knee to wall test

The knee to wall test was performed in a standing position facing a wall. In the test, the subjects lined up their heel and big toes with their feet on an imaginary line drawn on the floor to measure the distance from the wall (Figure 5A). The distance from the tip of the big toe to the wall was measured using a tape measure. While the knees were bending toward the wall, it was made sure that the heels did not come off the floor. Depending on the distance of the big toe from the wall, the maximum dorsiflexion of the ankle was measured (Figure 5B). The interrater reliability was r=0.99 (95% CL: 0.97-0.99), and the intrarater reliability was ICC=0.96 to 0.99, indicating high reliability.[32]

3) Foot pressure assessment

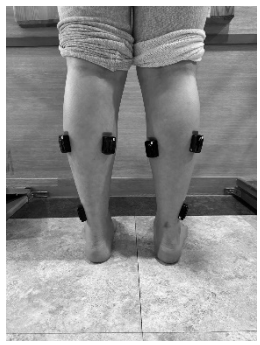
A smart insole (Pedisol®, R-C-SP0-Pedisol250, Spina Systems Co., Ltd., South Korea) with a built-in elec-

(A) Smart foot insole

(B) Pedisol application

Figure 6. Foot pressure measure equipment

(A) Trigno EMG sensor



(B) Place replacement

Figure 7. Electromyography

tronic sensor to detect foot pressure was used, which could be connected to a smartphone via Bluetooth (Figure 6A). In the Android setting, it measures the pressure on the wearer's foot once through the pedisol application (Figure 6B) installed on the smartphone and connected with the insole. In addition, foot pressure, trajectory of foot pressure center, and distance traveled can be checked in various assessment modes, such as two-foot stand, one-foot stand, sit-to-stand, functional arm extension test, 10-meter walk test, and 30-second walk test.[33)]

4) Muscle activation

The testing device used in this experiment was a surface electromyograph (Trigno EMG sensor, Delsys Inc., Boston, MA, USA) (Figure 7A) attached to the GCM and soleus involved in plantarflexion and knee flexion, as well as the tibialis anterior muscle involved in dorsiflexion (Figure 7B), to measure the maximal voluntary isometric contraction (MVIC). To collect accurate data, the attachment area was shaved with a razor and then wiped clean with sandpaper and an alcohol swab before the experiment. The electrode used to measure muscle activity was a circular Ag/AgCl surface electrode with a diameter of 2 cm. MVIC was measured with the lower extremity immobilized in a supine position on the examination table with a towel under the knee in ankle joint neutralization. The GCM was measured by applying manual resistance to the plantar surface of the foot during ankle plantar flexion with the knee extended, and the soleus was measured in the same manner with the knee bent. The tibialis anterior was measured by applying manual resistance to the dorsal surface of the foot with the knee bent during dorsiflexion in a sitting position.[31)] For the measurement of MVIC, the

Figure 8. Biodex balance system

contraction was maintained for 5 seconds, including a 1-second warm-up, and only the middle 3 seconds of the 5 second electromyographic signal, excluding the first and last 1-second, were recorded,[34] and then the triplicate values were averaged and quantified as root mean square (RMS), an amplitude-sensitive signal metric. To minimize the likelihood of muscle fatigue, sufficient breaks were taken between measurements.

5) Sway index

Balance was measured using a static balancing machine (Balance System 950-330, Biodex Medical Systems, USA) (Figure 8). This is a device that detects and quantifies sway when the subject stands on a scaffold with a sensor, and the measurement method is as follows. First, measurements were taken while standing with the feet shoulder-width apart in four different settings (standing on a hard footrest with eyes open, standing on a hard footrest with eyes closed, standing on a balance pad with eyes open, and standing on a balance pad with eyes closed). The sway index was measured three times for 20 seconds while standing in each setting. After the first measurement, a 10 second break was given. Test-retest reliability was r=0.95, and the interrater reliability was r=0.81.[35] The better the balance ability, the lower the sway index.

4. Statistical analysis

The general characteristics of the subjects were calculated as mean values and standard deviations using descriptive statistics. A non-parametric test was used as the data showed no normal distribution. A Wilcoxon signed-rank test was used to examine pre- and post-intervention differences within groups. Data were analyzed using Python ver. 3.10.12 (Python SW Foundation, Reston, Virginia, USA), and all statistical tests were performed at the 0.05 significance level.

Ⅲ. Results

1. Ankle range of motion

There was a statistically significant increase from 15.25±4.40° to 21.50±4.50° in the pre- to post-intervention ankle range of motion test and from 9.99±2.42cm to 11.18±2.34cm in the knee to wall test (p<0.05) (Table 2).

Table 2. Ankle Joint mobility (n=8)

Variables	pre	post	Change (post-pre)	z	p
ADROM (degree)	15.25±4.40[a]	21.50±4.50	6.25±4.68	-2.375	0.018*
KTW (cm)	9.99±2.42	11.18±2.34	1.19±0.97	-2.383	0.017*

p<0.05*, [a]Mean±standard deviation.
Note. ADROM: Ankle dorsi flexion range of motion test, KTW: Knee to wall test.

Table 3. Comparison of pre- and post-intervention foot pressure results (n=8) (unit : %)

Variables	pre	post	Change (post-pre)	z	*p*
Rt. toe	24.01±3.91[a]	20.97±2.84	-3.03±2.69	-1.575	0.012*
Lt. toe	23.04±2.46	21.57±2.70	-1.47±1.98	-1.155	0.047*
Rt. heel	24.79±2.58	26.99±2.44	2.20±2.05	-1.680	0.019*
Lt. heel	28.60±3.49	30.66±3.04	2.07±1.07	-1.890	0.048*

p<0.05*, [a]Mean±standard deviation.

Table 4. Comparison of muscle activation between groups (n=8) (unit : %MVIC)

Variables	pre	post	Change (post-pre)	z	*p*
RTA	18.69±20.64[a]	24.32±22.74	5.63±7.92	-1.312	0.018*
LTA	15.74±10.34	20.83±14.91	5.10±5.06	-0.840	0.040*
RMGCM	154.60±18.17	84.43±19.43	-70.16±111.93	-1.260	0.020*
LMGCM	115.20±66.28	76.74±30.39	-38.46±50.50	-2.205	0.027*
RLGCM	72.81±27.69	179.55±19.13	106.74±19.66	-1.890	0.048*
LLGCM	61.41±25.26	83.98±29.13	22.57±30.34	-1.785	0.074*
RSOL	57.03±32.45	129.97±89.55	72.94±81.03	-1.890	0.049*
LSOL	120.98±79.74	238.70±127.07	123.82±112.75	-1.995	0.045*

p<0.05*, [a]Mean±standard deviation.
Note. MVIC: Maximal voluntary isometric contraction, RTA: Right tibialis anterior, LTA: Left tibialis anterior, RMGCM: Right medial gastrocnemius, LMGCM: Left medial gastrocnemius, RLGCM: Right lateral gastrocnemius, LLGCM: Left lateral gastrocnemius, RSOL: Right soleus, LSOL: Left soleus.

2. Foot pressure

In the foot pressure test before and after intervention, the foot pressure decreased from 24.01±3.91% to 20.97±2.84% in the right forefoot, decreased from 23.04±2.46% to 21.57±2.70% in the left forefoot, increased from 24.79±2.58% to 26.99±2.44% in the right heel, and increased statistically significantly from 28.60±3.49% to 30.66±3.04% in the left heel (p<0.05) (Table 3).

3. Muscle activation

The right tibialis anterior activity increased from 18.69% MVIC pre-intervention to 24.32% MVIC post-intervention, showing a significant difference of 5.63% MVIC (p<0.05), and the left tibialis anterior activity increased from 15.74% MVIC pre-intervention to 20.83% MVIC post-intervention, showing a significant difference of 5.10% MVIC (p<0.05). The right medial GCM activity decreased from 154.60% MVIC pre-intervention to 84.43% MVIC post-intervention, showing a significant difference of 70.16% MVIC (p<0.05). The left medial GCM activity decreased from 115.20% MVIC pre-intervention to 76.74% MVIC post-intervention, showing a significant difference of 38.46% MVIC (p<0.05). The right lateral GCM activity increased from 72.81% MVIC pre-intervention to 179.55% MVIC post-intervention, showing a significant difference of 106.74% (p<0.05). The left lateral GCM activity increased from 61.41% MVIC pre-intervention to 83.98% MVIC post-intervention, showing a significant difference of 22.57% MVIC (p<0.05). The right soleus activity increased from 120.98% MVIC pre-intervention to 238.70% MVIC post-intervention, showing a significant difference of 123.82% MVIC (p<0.05). The left soleus activity increased from 120.98% pre-intervention to 238.70% MVIC post-intervention, showing a significant difference of 123.82% MVIC (p<0.05) (Table 4).

Table 5. Comparison between pre and post treatment mean value of Sway index in both groups (n=8)

Variables		pre	post	Change (post-pre)	z	p
Sway Index	1	0.30±0.06[a]	0.27±0.08	-0.03±0.08	-1.542	0.123
	2	0.70±0.11	0.58±0.12	-0.12±0.10	-2.366	0.018*
	3	0.50±0.10	0.42±0.06	-0.08±0.10	-2.201	0.028*
	4	1.73±0.21	1.53±0.15	-0.20±0.20	-2.524	0.012*

p<0.05*, [a]Mean±standard deviation.
Note. 1, standing on a firm pad with eyes open, 2, standing on a firm pad with eyes closed, 3, standing on a sponge pad with eyes open, 4, standing on a sponge pad with eyes close.

4. Sway index

The change in sway index from pre- to post-intervention was measured before and after the treatment intervention in setting 1 (standing on a hard footrest with eyes open), setting 2 (standing on a hard footrest with eyes closed), setting 3 (standing on a sponge with eyes open), and setting 4 (standing on a sponge with eyes closed). In setting 1, it decreased from 0.30 pre-intervention to 0.27 post-intervention, showing a significant difference of 0.03 (p<0.05), and in setting 2, it decreased from 0.70 pre-intervention to 0.58 post-intervention, showing a significant difference of 0.12 (p<0.05). In setting 3, it decreased from 0.50 pre-intervention to 0.42 post-intervention, showing a significant difference of 0.08 (p<0.05), and in setting 4, it decreased from 1.73 pre-intervention to 1.53 post-intervention, showing a significant difference of 0.20 (p<0.05)(Table 5).

Ⅳ. Discussion

In this study, GCM NMES and ankle control training were combined to determine foot function and static balance ability in healthy subjects. This study was conducted for a total of four weeks before and after the treatment intervention. Ankle mobility was measured by ankle range of motion and a knee to wall test; foot pressure by using smart insoles; and muscle activity of the tibialis anterior, GCM, and soleus by using surface electromyography equipment. The sway index was then measured using a static balancing machine. Foot function was defined to include ankle mobility, foot pressure, and muscle activity of the lower extremity.

The results of this study are as follows: First, ankle mobility showed an increase in the knee to wall test and ankle range of motion after the treatment intervention. A digital goniometer was used to secure consistent data on the ankle range of motion, and a knee to wall test with high reliability and validity was conducted for normal subjects to increase objectivity. Cheng et al. (2010)[30] found that an intervention method combining NMES and a rocker board could enhance the activation of concentric and eccentric muscle contractions of the muscles of the lower extremity, and Hung and Gross (1999)[34] found that ankle control training could improve postural control by increasing the alternating activity of the GCM and tibialis anterior. This was consistent with improvements in ankle mobility and static balance in this study.

Second, in the foot pressure test, the pressure in the forefoot decreased and the pressure in the heel increased. Choi & Chang (2022)[36] showed that ankle control training can induce elongation of the plantar flexor muscles to shift foot pressure posteriorly in a standing position. Kim et al. (2020)[20] showed that eccentric activation training of the ankle plantar flexor muscle can affect the vertical orientation of the subject's posture by activating the extensor muscles through an increase in ankle mobility and changes in foot pressure. This suggested that the interventions in this study would have a positive effect on bringing the knee and hip joints of the subjects to a neutral position. Lee (2019)[39] showed that shortening of the GCM length affected dynamic balance and foot pressure distribution anteriorly, and that changes in foot pressure through therapeutic interventions could im-

prove proprioception and thus balance ability.[36)]

Third, the sway index, a measure of static balance, showed a significant decrease in all settings except for standing on a hard footrest with eyes open. Balance board training, a method of proprioception training, was first proposed by Freeman et al.(1965)[35)] Since then, there have been many studies on its effectiveness, of which Hoffman & Gregory (1995)[36)] reported a reduction in body sway during postural balance control in normal adults after 10 weeks of proprioception training using balance boards. This was consistent with the results of this study, which seemed that ankle control training on the Rocker board improved balance ability. There are three factors impacting balance: vision, vestibular sensation, and proprioception.[37)] When vision or proprioception input is reduced, only vestibular sensation is left as the input for postural control, which can lead to a higher sway index.[35)] In this study, the sway index was measured on a balance pad with the eyes open or closed. The index had a significant decrease when measured with eyes closed, indicating that proprioception input among the three influencing factors on balance was improved, excluding vision.

Fourth, muscle activity showed a significant increase in the tibialis anterior, a significant decrease in the medial GCM, and a significant increase in the lateral GCM. Yoon et al. (2019)[38)] reported increased muscle activities in the peroneus longus and lateral GCM on stable ground and also in the tibialis anterior and medial GCM on unstable ground. Previous studies have shown that ankle control training on unstable ground increased the activity of the peroneus longus and lateral GCM muscles,[38)] thereby reducing anterior-posterior shifts in foot pressure.[30)] The present study showed an increase in muscle activity in the lateral GCM, suggesting that the intervention in this study should be beneficial for ankle stability as well as balance.[21)] When the lateral GCM is shortened, the calf bone exhibits posterior migration,[39)] which can affect ankle joint and knee joint motion, leading to foot shape deformity and excessive knee flexion.[40)] This study showed a significant increase in muscle activity in the soleus. The soleus forms the medial side of the Achilles tendon, making the inversion of the ankle and contributing to the stability of the ankle while balancing in a standing position.[41)] Of the lower extremity muscles, the soleus is constantly activated for postural control and is often used to lift the hips from a seated position.[42,43)] These suggest that the intervention in this study might have a positive effect on functional movements such as sitting and standing through muscle activation of the soleus.

A limitation of this study is that it was conducted with a single group and a small number of subjects, making it difficult to generalize the findings. In terms of foot function, this study was unable to measure ground reaction forces on foot morphology and the restoration of vertical alignment.

Therefore, this study demonstrated that GCM NMES combined with ankle control training could have impacts on foot function and balance. A future study would assess ground reaction force, including ankle mobility as well as foot shape changes to present more meaningful research data.

References

1. Ha NR, Kim MC, Han SK. The correlation between changes of ankle joint position sense and sway area through unstable surface training. The Journal of the Korea institute of electronic communication sciences. 2013;8(9):1383-9.
2. Neumann DA. Kinesiology of the musculoskeletal system: Foundations for rehabilitation. 3rd Edition. Mosby Elsevier. Saint Louis, Missouri, U.S.A. 2016.
3. Menz HB, Lord SR, Fitzpatrick RC. Acceleration patterns of the head and pelvis when walking on level and irregular surfaces. Gait & Posture. 2003;18(1):35-46.
4. Tsai LC, Yu B, Mercer VS, et al. Comparison of different structural foot types for measures of standing postural control. Journal of Orthopaedic & Sports Physical Therapy. 2006;36(12):942-53.
5. Lentell GL, Katzman LL, Walters MR. The relationship between muscle function and ankle stability. Journal of Orthopaedic & Sports Physical Therapy. 1990;11(12): 605-11.
6. Sahrmann S. Movement system syndrome of the foot and ankle: Movement system impairment syndromes of the extremities, cervical and thoracic spines. 1st Edition.

Mosby Elsevier. Saint Louis, Missouri, U.S.A. 2011: 439-80.
7. Hertel J. Functional instability following lateral ankle sprain. Sports medicine. 2000;29:361-71.
8. Muscolino JE. Know the body: Muscle, Bone, and Palpation Essentials. 1st Edition. Mosby Elsevier. Saint Louis, Missouri, U.S.A. 2011.
9. Haxton HA. Absolute muscle force in the ankle flexors of man. The Journal of Physiology. 1944;103(3):267-73.
10. Gajdosik RL, Vander Linden DW, Williams AK. Influence of age on length and passive elastic stiffness characteristics of the calf muscle-tendon unit of women. Physical Therapy. 1999;79(9):827-38.
11. Gribble PA, Hertel J, Denegar CR, et al. The effects of fatigue and chronic ankle instability on dynamic postural control. Journal of Athletic Training. 2004;39(4): 321-9.
12. Cummins EJ, Anson BJ. The structure of the calcaneal tendon (of achilles) in relation to orthopedic surgery, with additional observations on the plantaris muscle. Surgery, Gynecology & Obstetrics. 1946;83:107-16.
13. Hubbard TJ, Kramer LC, Denegar CR, et al. Contributing factors to chronic ankle instability. Foot & Ankle International. 2007;28(3):343-54.
14. Snow RE, Williams KR, Holmes GB, Jr. The effects of wearing high heeled shoes on pedal pressure in women. Foot & Ankle International. 1992;13(2):85-92.
15. Franklin ME, Chenier TC, Brauninger L, et al. Effect of positive heel inclination on posture. Journal of Orthopaedic & Sports Physical Therapy. 1995;21(2): 94-9.
16. Kwah LK, Harvey LA, Diong JH, et al. Half of the adults who present to hospital with stroke develop at least one contracture within six months: An observational study. Journal of Physiotherapy. 2012;58(1):41-7.
17. Lim TY, Ha SR, Choi YN, et al. The effects of eccentric stretching with weight bearing ankle rom and muscle strength in 20's women. Journal of Korean Society Neurotherapy. 2015;19(3):29-33.
18. Roig M, Macintyre DL, Eng JJ, et al. Preservation of eccentric strength in older adults: Evidence, mechanisms and implications for training and rehabilitation. Experimental Gerontology. 2010;45(6):400-9.
19. Laroche D, Joussain C, Espagnac C, et al. Is it possible to individualize intensity of eccentric cycling exercise from perceived exertion on concentric test? Archives of Physical Medicine and Rehabilitation. 2013;94(8): 1621-7.
20. Kim DW, Kim JH, Kim JH. Effects of eccentric activation training of plantar flexors for the patients with stroke. Journal of Korean Society for Neurotherapy. 2020;24(1): 33-9.
21. Choi YS, Chang WN. Effects of Ankle Control Training using NMES on Ankle Joint Mobility and Balance in a Healthy Adult: A Single Case Study. Journal of Korean Society for Neurotherapy. 2022;26(3):19-29.
22. Yang YR, Mi PL, Huang SF, et al. Effects of neuromuscular electrical stimulation on gait performance in chronic stroke with inadequate ankle control-a randomized controlled trial. PLoS One. 2018;13(12): e0208609.
23. Lee JH. Current Electrotherapy. 1st Edition. Daehakseolim. Seoul. 2010.
24. Hur Y. The effects on spasticity, range of motion, balance on combining active-stretching exercise of plantarflexor on ankle with fes in the patients with stroke. Dissertation of Master's Degree Yongin University. 2013.
25. Wright PA, Durham S, Ewins DJ, et al. Neuromuscular electrical stimulation for children with cerebral palsy: a review. Archives of Disease in Childhood. 2012;97: 364-71.
26. Kobravi HR, Farzaneh Y, Majd MF, et al. A human interactive hybrid fes-robotic system applicable to improvement of foot drop after stroke: Case report of a patient with chronic stroke. Archives of Bone and Joint Surgery. 2020;8(6):744-7.
27. Sharif F, Ghulam S, Malik AN, et al. Effectiveness of functional electrical stimulation (fes) versus conventional electrical stimulation in gait rehabilitation of patients with stroke. Journal of College of Physicians and Surgeons Pakistan. 2017;27(11):703-6.
28. Mahadevappa M, Shendkar C, Lenka P, et al. Modelling a bci system to estimate fes stimulation intensity for individual stroke survivors in foot drop cases. Biomedical Engineering/Biomedizinische Technik. 2013;58(SI-1-Track-A):000010151520134031.
29. Bae SB, Lee J, Lee BH. Effect of an emg–fes interface on ankle joint training combined with real-time feedback on balance and gait in patients with stroke hemiparesis. Healthcare (Basel). 2020;8(3):292.

30. Cheng JS, Yang YR, Cheng SJ, et al. Effects of combining electric stimulation with active ankle dorsiflexion while standing on a rocker board: A pilot study for subjects with spastic foot after stroke. Archives of Physical Medicine and Rehabilitation. 2010;91(4):505-12.
31. Lee WH. Effects of gastrocnemius muscle length on the dynamic balance and antero-posterior pressure distribution of foot. Journal of the Korea Academia-Industrial cooperation Society. 2019;20(6):150-7.
32. Bennell K, Talbot R, Wajswelner H, et al. Intra-rater and inter-rater reliability of a weight-bearing lunge measure of ankle dorsiflexion. Australian Journal of Physiotherapy. 1998;44(3):175-80.
33. Seo TW, Lee JY, Lee BH. The reliability test of a smart insole for gait analysis in stroke patients. Journal of Korean Academy of Physical Therapy Science. 2022; 29(1):30-40.
34. Hung YJ, Gross MT. Effect of foot position on electromyographic activity of the vastus medialis oblique and vastus lateralis during lower-extremity weight-bearing activities. Journal of Orthopaedic & Sports Physical Therapy. 1999;29(2):93-102.
35. Cachupe WJ, Shifflett B, Kahanov L, et al. Reliability of biodex balance system measures. Measurement in Physical Education and Exercise Science. 2001;5(2): 97-108.
36. Hoffman M, Payne VG. The effects of proprioceptive ankle disk training on healthy subjects. Journal of Orthopaedic & Sports Physical Therapy. 1995; 21(2): 90-3.
37. Cimadoro G, Paizis C, Alberti G, et al. Effects of different unstable supports on emg activity and balance. Neuroscience Letters. 2013;548:228-32.
38. Yoon SR, Kim JW, Song DE, et al. Effect of various support surfaces on activation of tibialis anterior, peroneus longus, and gastrocnemius muscles during squat performance. Journal of Musculoskeletal Science and Technology. 2019;3(2):31-7.
39. Kwon OS, Kang YH, Lim JH, et al. The effects on erector spine muscles and calf muscle activity according to book bag handling styles and footwear. Journal of the Korean Academy of Clinical Electrophysiology. 2011;9(1): 29-34.
40. Sagong WW, An DH. Postural strategy by the difference of shoe heel height during quiet standing on an unstable surface. Physical Therapy Korea. 2014;21(2):28-36.
41. Lentell G, Katzman LL, Walters MR. The relationship between muscle function and ankle stability. Journal of Orthopaedic & Sports Physical Therapy. 1990;11(12): 605-11.
42. Goulart F, Valls-Solé J. Reciprocal changes of excitability between tibialis anterior and soleus during the sit-to-stand movement. Experimental Brain Research. 2001;139: 391-7.
43. Khemlani M, Carr J, Crosbie W. Muscle synergies and joint linkages in sit-to-stand under two initial foot positions. Clinical Biomechanics. 1999;14(4):236-46.