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Original Paper

Development of High-frequency Magnetic Stimulator to Induce Stronger Knee Extension Torque

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Key words: repetitive peripheral magnetic stimulation, torque, strengthening muscles, prevention of muscle atrophy, quadriceps

Abstract

This study aimed to clarify whether higher knee extension torque (KET) can be induced by a newly manufactured magnetic stimulator (new equipment) as compared to the conventional equipment and an electrical stimulator. Thirteen healthy young men voluntarily participated in the study. The new and conventional equipment were both used for repetitive peripheral magnetic stimulation (r-PMS), and belt electrode skeletal muscle electrical stimulation was used for neuromuscular electrical stimulation (NMES) at maximal intensity within the range of tolerable pain. The right vastus lateralis (VL) was magnetically stimulated, and the entire right quadriceps femoris (QF) was electrically stimulated to compare the KET induced by each stimulation. The right rectus femoris (RF) was also magnetically stimulated to compare the KET between the two magnetic stimulators. The KET induced by r-PMS using both pieces of equipment on the VL was higher than that induced by NMES. An average of 16.4% of the maximum voluntary contraction (MVC) in the entire QF was induced by the new equipment that applied only to the VL. The KET induced by the new equipment to the RF was higher than that induced by the conventional equipment. An average of 13.5% of the MVC in the entire QF was induced by the new equipment when applied only to the RF. In conclusion, r-PMS using the newly manufactured magnetic stimulator may prevent muscle weakness caused by disuse.

1. Introduction

Ageing causes muscle weakness in humans[1], which leads to a decrease in physical function[2,3], risk of falls, and an increased mortality rate[4,5]. Therefore, it is essential to prevent muscle weakness due to ageing and to increase muscle power from the viewpoint of healthy life expectancy. Resistance exercises strengthen muscles in older adults to maintain good health and physical function[6,7]. However, since each individual must actively perform resistance exercises, their effect depends on the individual's motivation to perform the exercises and maintain daily efforts. Therefore, it is often difficult for older adults without an instructor or persons with dementia to continue the resistance exercises for an extended period, and easier ways to

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increase or maintain muscle power are needed.

Neuromuscular electrical stimulation (NMES) was introduced as a convenient modality for maintaining or increasing muscle power[8]. The effects of increasing muscle power using NMES have been reported in many studies concerning stroke, respiratory or cardiovascular diseases, and older adults[9-12]. However, nociceptors are often so overly stimulated that they cause severe pain and discomfort to the participants because high stimulation intensity is required for strengthening muscles using NMES[12-14]. Magnetic stimulation has received much attention in recent years as an alternative method to NMES because the contraction of deep muscles can be induced with less pain[15-18]. Since nociceptors in the skin are not excited during muscle contraction induced by magnetic stimulation[18], interest in repetitive peripheral magnetic stimulation (r-PMS) is increasing as a novel method of muscle strengthening. In previous studies, r-PMS has been applied mainly to the quadriceps femoris (QF) in healthy individuals and patients with stroke, postoperative total hip arthroplasty, chronic obstructive pulmonary diseases, and other conditions. r-PMS has been reported to be effective in strengthening muscles under these conditions[19-23].

In the past, most of the magnetic stimulators utilized for strengthening muscles were equipment developed for transcranial magnetic stimulation, which stimulated the cerebrum[19-23]. When high-intensity and high-frequency stimulation was applied using this equipment, the coil generated heat of 40 °C or higher, making it difficult to continue stimulation for several minutes or longer. When the coil generates large amounts of heat, it must be allowed to cool for an extended time[19,20]. To solve this problem, an air-cooled magnetic stimulator (*conventional equipment*) for r-PMS was developed in Japan[24]. Although it was mainly used for functional improvement in the upper extremities[25-27], there have been a few reports that muscle strengthening via r-PMS could be effective in large muscles such as those of the lower extremities[28]. Therefore, we developed a prototype of a high-frequency magnetic stimulator (*new equipment*) that can generate a slightly higher magnetic field intensity than that of the conventional equipment while suppressing heat generation for an extended period[29].

As a preliminary step to examine its clinical usefulness, we investigated whether the knee extension torque (KET) induced by the new equipment can be higher than that induced by the conventional equipment or an electrical stimulator. Based on the results of this study, it is expected that muscle contraction in the lower extremities induced by the new equipment could lead to the prevention of muscle atrophy due to disuse and to the maintenance or improvement of muscle strength in older adults.

2. Methods

2.1 Subjects

Thirteen healthy young men (mean age, 21.5 ± 4.1 years) without a history of orthopedic or central nervous system diseases voluntarily participated in this study. The sample size required for the study was predetermined using G*Power (version 3.1.9.7, Germany). To determine sample sizes using *a priori* power analysis, we set the significance criterion at $\alpha = 0.05$, statistical power at $(1-\beta) = 0.80$, large effect size at Cohen's $f = 0.40$, and significance level at $p = 0.05$. As a result, the required sample size was 12 individuals, and 13 volunteers were recruited to account for drop-outs.

The study was conducted per the principles of the Declaration of Helsinki. The purpose of the study was explained in detail to all participants, both verbally and in writing. Written informed consent was obtained from all participants after their understanding of the research content was confirmed. This study was approved by the Ethics Committee, Kawasaki University of Medical Welfare (No. 19-072).

2.2 Methods of magnetic stimulation

The vastus lateralis (VL) has been used as the stimulation site in most previous studies concerning r-PMS[19,20,22,29,30]. The right VL was selected as the site for r-PMS in this study to compare the KET induced by three stimulation methods: using the conventional equipment (Pathleader®, IFG Co., Ltd., Sendai, Japan), using the new equipment (prototype, OG Wellness Technologies Co., Ltd., Okayama, Japan), and using NMES. Additionally, the right rectus femoris (RF) was magnetically stimulated to compare the KET between the two pieces of equipment.

Before measuring the KET, we searched for a site where the greatest muscle contraction force was induced by moving the probe of the conventional equipment. The optimal site for the VL was marked on the skin between the proximal one-third and distal one-third of the line connecting the anterior superior iliac spine and the lateral edge of the base of the patella, as previously reported[29]. Similarly, the optimal site for the RF was marked on the skin between the proximal one-third and distal one-third of the line connecting the anterior superior iliac spine and the centre of the base of the patella[20,22]. To measure the KET, the mark was aligned with the centre of the coil, and the long axis direction of the coil was set parallel to the long axis of the thigh.

The maximum magnetic flux density just below the surface of the probe was 1.11 T for the new equipment and 0.92 T for the conventional equipment. The size of the probe and the surface area of the coil inside the probe are listed in Table 1. The stimulation frequency was set to 30 Hz, the stimulation period was 3 s, and the rest period was 2 s. Five stimulations were given isometrically at the maximum intensity within the range of tolerable pain.

Table 1 Parameters of the magnetic stimulators

	Intensity below the surface of the probe (Tesla)	Maximal output intensity (Tesla)	Surface area of the coil (cm^2)	Size of the probe (cm)
Conventional equipment	0.92	1.00	10.1	10.5 × 12.5
New equipment	1.11	1.30	18.2	19.5 × 21.5

2.3 Methods of electrical stimulation

NMES was performed using the G-TES® equipment (Homer Ion Co., Ltd., Tokyo, Japan) utilized in the belt electrode skeletal muscle electrical stimulation in this study. The belt electrodes were wrapped around the most proximal part of the right thigh and just above the right base of the patella to induce contraction of the entire QF. To prevent the knee flexors from contracting, two 12.5-cm-wide Thera-Bands® (SAKAI Medical Co., Ltd., Tokyo, Japan) were attached between the posterior surface of the thigh and the belt electrodes with surgical tape as the insulator. The proximal band was located from the center of the muscle belly in the tensor fasciae latae to the center of the muscle belly in the adductor longus, and the distal band, from the lateral edge of the biceps femoris to the medial edge of the semimembranosus. The intensity gradually increased from minimal to maximal stimulation within the range of tolerable pain[15,19]. The stimulation frequency was set at 30 Hz with a 2 s ramp-up, a stimulation period of 3 s, and a rest period of 2 s. Five stimulations were performed.

2.4 Measurements of knee extension torque

A multi-mode computerised robotic dynamometer (BIODEX System 3®, Biodex Medical Systems, Inc., Shirley, NY, USA) was used to measure the KET. The participants were instructed to sit on a chair with their right knee and hip joints flexed at 75°. The trunk and pelvic girdle were tied to the seat, and the distal end of the right lower leg was strapped to the attachment. First, the maximum voluntary contraction (MVC) of the right knee extensors for 3 s was measured twice with a break of 5 s. After measuring the MVC, the KET was evaluated five times during each stimulation method. The participants were instructed to relax their right lower extremity, upper extremities, and trunk. The order of measurement of KET induced by the three stimulation methods was randomised.

2.5 Evaluation of pain intensity

After measuring the KET induced by each stimulation method, the pain intensity during stimulation was evaluated using the visual analogue scale (VAS). The participants were asked to mark a dot on a 10-cm straight line drawn on paper. The left end of the line was determined to be "0 = no pain", and the right end to be "10 = extremely intense pain". The value was rounded to one decimal place.

2.6 Data processing

The mean KET was calculated for an interval of 1000 ms, from 1500 ms to 500 ms before the time when the waveform returned to baseline at the end of contraction (Figure 1). Three data points, excluding the largest and smallest values, were used to compare the KET induced by each stimulation method. The relative KET was calculated by dividing KET by MVC (%MVC).

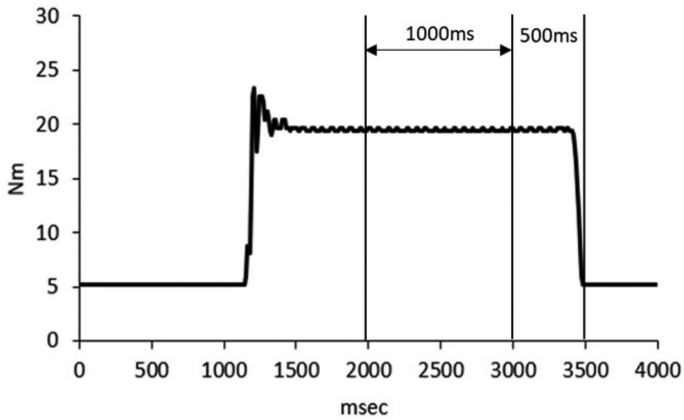

Figure 1 Waveform of knee extension torque and data processing

A raw waveform indicates the knee extension torque (KET) when the vastus lateralis (VL) was stimulated by the prototype high-frequency magnetic stimulator (new equipment). The data used for analysis were the mean KET calculated for the interval from 1500 ms to 500 ms before the waveform returned to baseline at the end of the contraction.

2.7 Statistical analysis

Repeated measures analysis of variance (ANOVA) was used to compare the %MVC of the VL induced by the two magnetic stimulators and that of the QF induced by NMES. If the results of the repeated measures ANOVA were significant, the Bonferroni method was used for multiple comparisons. The Wilcoxon signed-rank test was used to compare the %MVC of the RF induced by the two magnetic stimulators. The VAS score was compared between the three stimulation methods using a repeated measures ANOVA followed by the Bonferroni post hoc test. Statistical analyses were performed using SPSS ver. 22.0 (IBM Corp., Armonk, NY, USA), and p-values < 0.05 were considered statistically significant.

3. Results

3.1 Comparison of knee extension torque by each stimulation method

All participants received r-PMS at the maximum magnetic flux density (maximum intensity) of both stimulators without experiencing severe pain. Because the new equipment's probe area was larger than that of the conventional equipment, the new equipment's probe was occasionally in contact with the seat or attachment during stimulation of the VL (Figure 2). The mean values of the KET induced by each stimulation method are listed in Table 2. There were statistically significant differences between the %MVC of the VL induced by the two magnetic stimulators and that of the entire QF induced by NMES ($F(2,24) = 18.847$, $p < 0.01$, $\eta^2 = 0.611$). Subsequent multiple comparisons showed that the values induced by the two magnetic stimulators were significantly higher than those induced by NMES. However, there was no significant difference between the values induced by the new and conventional equipment (Figure 3). On the contrary, when comparing the %MVC during r-PMS of the RF, the value induced by the new equipment was statistically significantly higher than that of the conventional equipment ($p < 0.05$; Figure 4).

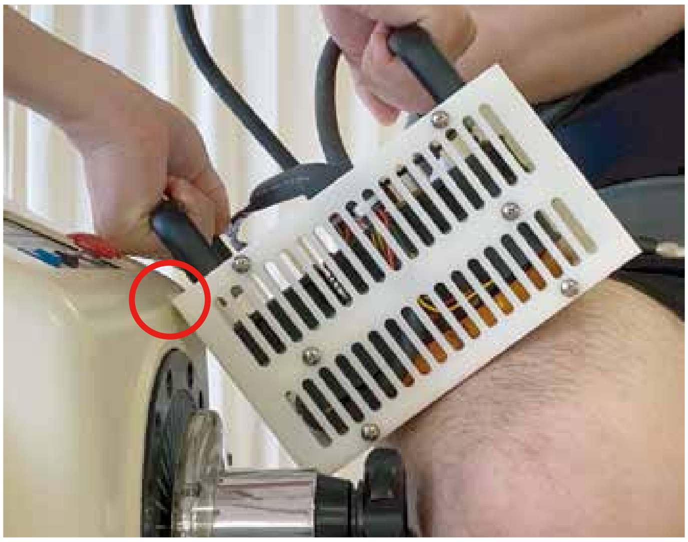

Figure 2 Probe of the prototype high-frequency magnetic stimulator (new equipment) and site of vastus lateralis stimulation

The red circle indicates the contact between the dynamometer and probe of the new equipment.

Table 2 Knee extension torque induced by each stimulation method

Muscle	Stimulator	KET (Nm)	Mean %MVC (%)	SD of %MVC (%)
VL	Conventional equipment	39.6 ± 15.3	17.6**	7.5
VL	New equipment	38.0 ± 15.8	16.4**	6.6
Quadriceps	NMES	13.2 ± 9.9	5.9	4.7
RF	Conventional equipment	23.8 ± 12.3	10.5	5.7
RF	New equipment	31.2 ± 15.0	13.5†	5.7
RF	MVC	234.7 ± 51.7		

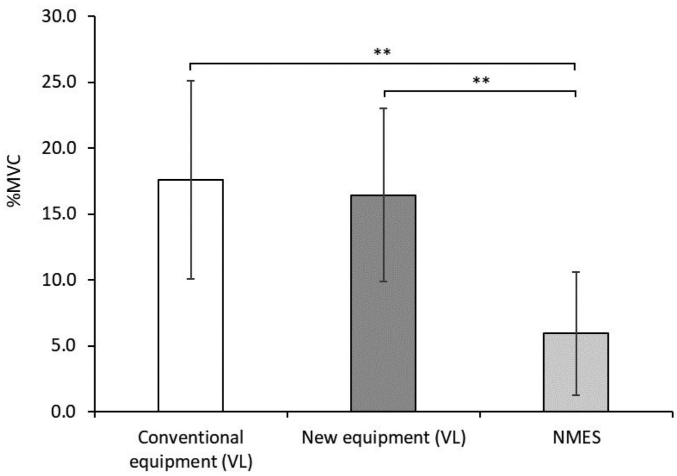

Figure 3 Knee extension torque (%MVC) of the vastus lateralis induced by three stimulators

The bar graphs show the mean and standard deviation of the relative knee extension torque (KET).
Relative KET (%MVC) was calculated by dividing the KET by the maximum voluntary contraction (MVC).
VL: vastus lateralis, NMES: neuromuscular electrical stimulation
** $p < 0.01$

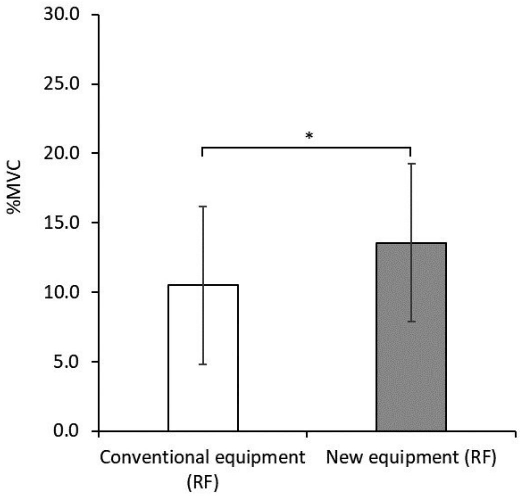

Figure 4 Knee extension torque (%MVC) of the rectus femoris induced by conventional and new equipment
The bar graphs show the mean and standard deviation of the relative knee extension torque (KET).
Relative KET (%MVC) was calculated by dividing KET by the maximum voluntary contraction (MVC).
RF: rectus femoris, NMES: neuromuscular electrical stimulation
* $p < 0.05$

3.2 Comparison of the pain intensity during each stimulation method

There were significant differences in the mean VAS scores between the stimulation methods (F (1.318, 15.811) = 21.067, $p < 0.01$, $\eta^2 = 0.637$). Subsequent multiple comparisons showed that the values achieved during r-PMS were significantly lower than those during NMES ($p < 0.01$; Figure 5).

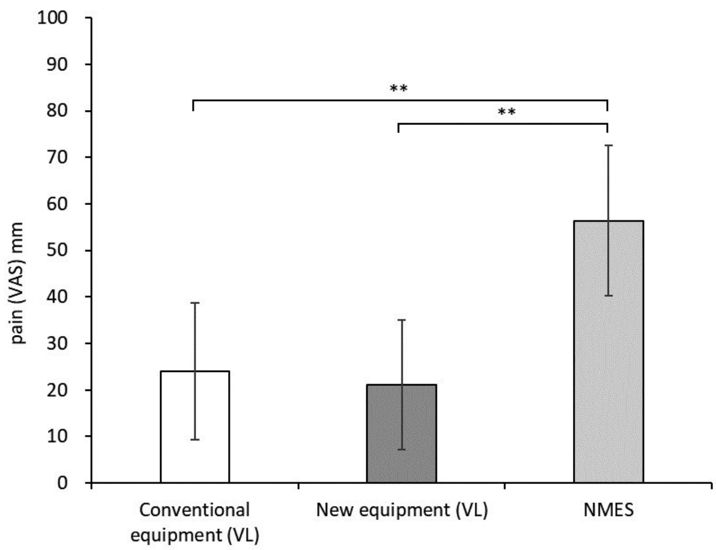

Figure 5 Pain intensity during magnetic stimulation of vastus lateralis and electrical stimulation of quadriceps femoris
The bar graphs show the mean and standard deviation of the pain intensity.
VL: vastus lateralis, NMES: neuromuscular electrical stimulation
** $p < 0.01$

4. Discussion

The results of this study revealed that the KET of the VL induced by r-PMS was larger than that of the entire QF induced by NMES, and the pain experienced by participants was more severe during NMES, consistent with the results of previous studies[15,26]. High-intensity NMES has been reported to excite nociceptors (A-delta and C-fibers) in the skin, causing severe pain and discomfort in humans[12-14]. It has also been reported that 8/18 subjects withdrew due to pain and discomfort during a study attempting intervention using NMES[31]. Similarly, NMES caused pain and discomfort to the participants in this study; thus, it was not possible to stimulate with higher intensity, and as a result, the KET decreased. In other words, r-PMS was confirmed to be an excellent method for inducing strong muscle contraction without pain compared to NMES. Additionally, r-PMS can be applied while the participant is clothed because the magnetic field passes through clothing, and there is no need to attach electrodes directly to the body, as with NMES[18,32]. Therefore, r-PMS is undoubtedly a more convenient modality for inducing muscle contraction than NMES.

There was no significant difference in the KET of the VL between the conventional and new equipment in this study. This result can be attributed to three factors: first, the sub-branches of the VL branch arising from the femoral nerve trunk stimulated with the new equipment may have been the same as the sub-branches stimulated with the conventional equipment; in fact, both the superficial proximal and deep proximal sub-branches are known to run directly below the optimal VL stimulation site[33]. If both sub-branches were supramaximally stimulated, the stimulation of the intramuscular clustered motor nerve endings (motor points) under their innervation would be negligible. The depth reached by the magnetic field of the new equipment was similar to that of the conventional equipment; therefore, the KET may have been almost the same strength[29]. However, it remains questionable whether the conventional equipment can stimulate the deep proximal sub-branch. Second, the optimal stimulation site for the new equipment may have differed from that of the conventional equipment. Anatomically, there are no sub-branches other than the superficial proximal and deep proximal sub-branches near this site[33]. Third, it is presumed that the effective magnetic intensity did not reach the intramuscular nerve when using the new equipment; since the new equipment's probe was larger than that of the conventional equipment, it was occasionally in contact with the seat or the dynamometer attachment. Therefore, it cannot be denied that the magnetic flux density from the probe did not induce effective muscle contraction because the probe could not be placed precisely perpendicular to the VL. It is supposed that the KETs were almost the same, as there was no difference in the maximum magnetic flux density on the surface of the muscle between the two types of equipment.

Considering the muscles in which the stimulation process was not affected by the size of the probe of the new equipment, we also compared the r-PMS of the RF in this study. It became easier to place the probe perpendicular to the muscle when the RF was the target muscle for stimulation. The results showed that the KET induced by the new equipment was larger than that induced by the conventional equipment. Previous studies have reported that the higher the r-PMS intensity, the stronger the KET induced[15], and that the larger the magnetic coil, the greater the induced current amplitude and the deeper the reach[18]. These reports suggest that the stimulation induced by the new equipment with a higher stimulation intensity and a larger coil size may have reached deeper levels. Since the two sub-branches of the RF branch (superior sub-branch and inferior sub-branch) were reported to enter the RF on the posterior surface[33], it is unlikely that r-PMS directly stimulated these sub-branches. Therefore, it is possible that the new equipment stimulated more motor points in the muscle than did the conventional equipment. It has been reported that muscle atrophy of the paralysed RF in stroke patients is prevented by therapeutic intervention using conventional equipment[28]. Because the KET induced by the new equipment during stimulation of the RF was higher than that induced by the conventional equipment, the new equipment can be expected to prevent muscle atrophy more effectively than conventional equipment.

In this study, an average of 16.4% of the MVC in the entire QF was induced by stimulating only the VL, and 13.5% was induced by stimulating only the RF. Assuming that the strength of the VL is one-third the strength of the entire QF[34], this value may correspond to more than 45% of the MVC of the VL alone. Similarly, assuming that the strength of the RF is one-ninth the strength of the entire QF[34], this value may correspond to about 100% of the MVC of the RF alone. The intensity of resistance exercises commonly used for strengthening muscles in older adults has been reported to be 40%-85% of the MVC when performed 1-3 times per week for 6-52 weeks[6]. Therefore, the contractile force obtained in this study is sufficient to prevent muscle weakness caused by disuse. r-PMS is expected to become a therapeutic method for maintaining or increasing muscle power in older adults. Future research on the effectiveness of r-PMS in strengthening muscles is required.

One of the limitations of this study is that the probe of the magnetic stimulator was in contact with the seat and the attachment of the dynamometer during stimulation of the VL. Another limitation was the inability to evaluate the degree of muscle contraction other than the target muscle belonging to the QF during r-PMS. Moreover, another challenge is that the subjects who participated in this experiment were healthy young adults, while the target group for treatment is the elderly. Additional studies of magnetic stimulation in the elderly are needed. In the future, it will be necessary to clarify the relationship between the KET during r-PMS and the characteristics of the subjects.

The KET induced in the RF by the new equipment was higher than that induced by the conventional equipment. It was suggested that r-PMS using the new equipment may prevent muscle weakness caused by disuse. It is also expected to contribute to maintaining muscle power in older adults.

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Competing Interests

The Kawasaki University of Medical Welfare has signed a joint research agreement with OG Wellness Technologies Co., Ltd. We asked the company to manufacture a piece of equipment and received a total of ¥2,398,000 in research funding over 3 years.

References

1. Manini TM, Hong SL and Clark BC : Aging and muscle: A neuron's perspective. *Current Opinion in Clinical Nutrition and Metabolic Care*, 16(1), 21-26, 2013.
2. Janssen I, Heymsfield SB and Ross R : Low relative skeletal muscle mass (sarcopenia) in older persons is associated with functional impairment and physical disability. *Journal of the American Geriatrics Society*, 50(5), 889-896, 2002.
3. Delmonico MJ, Harris TB, Visser M, Park SW, Conroy MB, Velasquez-Mieyer P, Boudreau R, Manini TM, Nevitt M, ...Goodpaster BH : Longitudinal study of muscle strength, quality, and adipose tissue infiltration. *The American Journal of Clinical Nutrition*, 90(6), 1579-1585, 2009.
4. de Rekeneire N, Visser M, Peila R, Nevitt MC, Cauley JA, Tylavsky FA, Simonsick EM and Harris TB : Is a fall just a fall: Correlates of falling in healthy older persons. The health, aging and body composition study. *Journal of the American Geriatrics Society*, 51(6), 841-846, 2003.

5. Ruiz JR, Sui X, Lobelo F, Morrow JR Jr, Jackson AW, Sjöström M and Blair SN : Association between muscular strength and mortality in men: Prospective cohort study. *BMJ*, 337(7661), a439, 2008.
6. Peterson MD, Rhea MR, Sen A and Gordon PM : Resistance exercise for muscular strength in older adults: A meta-analysis. *Ageing Research Reviews*, 9(3), 226-237, 2010.
7. Peterson MD, Sen A and Gordon PM : Influence of resistance exercise on lean body mass in aging adults: A meta-analysis. *Medicine and Science in Sports and Exercise*, 43(2), 249-258, 2011.
8. Avila MA, Brasileiro JS and Salvini TF : Electrical stimulation and isokinetic training: Effects on strength and neuromuscular properties of healthy young adults. *Brazilian Journal of Physical Therapy*, 12(6), 435-440, 2008.
9. Jung KS, In TS and Cho HY : Effects of sit-to-stand training combined with transcutaneous electrical stimulation on spasticity, muscle strength and balance ability in patients with stroke: A randomized controlled study. *Gait & Posture*, 54, 183-187, 2017.
10. Chen RC, Li XY, Guan LL, Guo BP, Wu WL, Zhou ZQ, Huo YT, Chen X and Zhou LQ : Effectiveness of neuromuscular electrical stimulation for the rehabilitation of moderate-to-severe COPD: A meta-analysis. *International Journal of Chronic Obstructive Pulmonary Disease*, 11, 2965-2975, 2016.
11. Jones S, Man WD, Gao W, Higginson IJ, Wilcock A and Maddocks M : Neuromuscular electrical stimulation for muscle weakness in adults with advanced disease. *The Cochrane Database of Systematic Reviews*, 10(10), CD009419, 2016.
12. de Oliveira TMD, Felício DC, Filho JE, Durigan JLQ, Fonseca DS, José A, Oliveira CC and Malaguti C : Effects of whole-body electromyostimulation on function, muscle mass, strength, social participation, and falls-efficacy in older people: A randomized trial protocol. *PloS One*, 16(1), e0245809, 2021.
13. Chae J and Hart R : Comparison of discomfort associated with surface and percutaneous intramuscular electrical stimulation for persons with chronic hemiplegia. *American Journal of Physical Medicine & Rehabilitation*, 77(6), 516-522, 1998.
14. Adriaensen H, Gybels J, Handwerker HO and Van Hees J : Response properties of thin myelinated (A-delta) fibers in human skin nerves. *Journal of Neurophysiology*, 49(1), 111-122, 1983.
15. Han TR, Shin HI and Kim IS : Magnetic stimulation of the quadriceps femoris muscle: Comparison of pain with electrical stimulation. *American Journal of Physical Medicine & Rehabilitation*, 85(7), 593-599, 2006.
16. Amassian VE, Maccabee PJ and Cracco RQ : Focal stimulation of human peripheral nerve with the magnetic coil: A comparison with electrical stimulation. *Experimental Neurology*, 103(3), 282-289, 1989.
17. Ito T, Tsubahara A and Watanabe S : Use of electrical or magnetic stimulation for generating hip flexion torque. *American Journal of Physical Medicine & Rehabilitation*, 92(9), 755-761, 2013.
18. Barker AT : An introduction to the basic principles of magnetic nerve stimulation. *Journal of Clinical Neurophysiology*, 8(1), 26-37, 1991.
19. Bustamante V, Casanova J, López de Santamaría E, Mas S, Sellarés J, Gea J, Gáldiz JB and Barreiro E : Redox balance following magnetic stimulation training in the quadriceps of patients with severe COPD. *Free Radical Research*, 42(11-12), 939-948, 2008.
20. Bustamante V, López de Santa María E, Gorostiza A, Jiménez U and Gáldiz JB : Muscle training with repetitive magnetic stimulation of the quadriceps in severe COPD patients. *Respiratory Medicine*, 104(2), 237-245, 2010.
21. Yang SS, Jee S, Hwang SL and Sohn MK : Strengthening of quadriceps by neuromuscular magnetic stimulation in healthy subjects. *PM & R*, 9(8), 767-773, 2017.
22. Baek J, Park N, Lee B, Jee S, Yang S and Kang S : Effects of repetitive peripheral magnetic stimulation over vastus lateralis in patients after hip replacement surgery. *Annals of Rehabilitation Medicine*, 42(1), 67-75, 2018.
23. Kinoshita S, Ikeda K, Hama M, Suzuki S and Abo M : Repetitive peripheral magnetic stimulation combined with intensive physical therapy for gait disturbance after hemorrhagic stroke: An open-label case series. *International Journal of Rehabilitation Research*, 43(3), 235-239, 2020.

24. Suzuki K, Hiraoka T, Tsubahara A, Ito T, Izumi S, Yashima K and Iwachidou N : Considerations for safety of high frequency repetitive peripheral magnetic stimulation of skeletal muscles in rats: Assessment by histological analysis of muscles and biochemical blood tests. *Japanese Journal of Comprehensive Rehabilitation Science*, 6, 56-63, 2015.
25. Fujimura K, Kagaya H, Endou C, Ishihara A, Nishigaya K, Muroguchi K, Tanikawa H, Yamada M, Kanada Y and Saitoh E : Effects of repetitive peripheral magnetic stimulation on shoulder subluxations caused by stroke: A preliminary study. *Neuromodulation*, 23(6), 847-851, 2020.
26. Abe G, Oyama H, Liao Z, Honda K, Yashima K, Asao A and Izumi SI : Difference in pain and discomfort of comparable wrist movements induced by magnetic or electrical stimulation for peripheral nerves in the dorsal forearm. *Medical Devices*, 13, 439-447, 2020.
27. Obayashi S and Takahashi R : Repetitive peripheral magnetic stimulation improves severe upper limb paresis in early acute phase stroke survivors. *NeuroRehabilitation*, 46(4), 569-575, 2020.
28. Suzuki K, Ito T, Okada Y, Hiraoka T, Hanayama K and Tsubahara A : Preventive effects of repetitive peripheral magnetic stimulation on muscle atrophy in the paretic lower limb of acute stroke patients: A pilot study. *Progress in Rehabilitation Medicine*, 5, 20200008, 2020.
29. Tsubahara A, Kamiue M, Ito T, Kishimoto T and Kurozumi C : Measurement of maximal muscle contraction force induced by high-frequency magnetic stimulation: A preliminary study on the identification of the optimal stimulation site. *Japanese Journal of Comprehensive Rehabilitation Science*, 12. 27-31, 2021.
30. Madariaga VB, Manterola AG, Miró EL and Iturri JB : Magnetic stimulation of the quadriceps: Analysis of 2 stimulators used for diagnostic and therapeutic applications. *Archivos de Bronconeumologia*, 43(7), 411-417, 2007.
31. Chae J, Bethoux F, Bohine T, Dobos L, Davis T and Friedl A : Neuromuscular stimulation for upper extremity motor and functional recovery in acute hemiplegia. *Stroke*, 29(5), 975-979, 1998.
32. Barker AT, Freeston IL, Jalinous R and Jarratt JA : Magnetic stimulation of the human brain and peripheral nervous system: An introduction and the results of an initial clinical evaluation. *Neurosurgery*, 20(1), 100-109, 1987.
33. Botter A, Oprandi G, Lanfranco F, Allasia S, Maffiuletti NA and Minetto MA : Atlas of the muscle motor points for the lower limb: Implications for electrical stimulation procedures and electrode positioning. *European Journal of Applied Physiology*, 111(10), 2461-2471, 2011.
34. Toumi H, Best TM, Mazor M, Coursier R, Pinti A and Lespessailles E : Association between individual quadriceps muscle volume/enthesis and patello femoral joint cartilage morphology. *Arthritis Research & Therapy*, 16(1), R1, 2014.