Video game-based neuromuscular electrical stimulation system for calf muscle training: A case study

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Abstract

A video game-based training system was designed to integrate neuromuscular electrical stimulation (NMES) and visual feedback as a means to improve strength and endurance of the lower leg muscles, and to increase the range of motion (ROM) of the ankle joints. The system allowed the participants to perform isotonic concentric and isometric contractions in both the plantarflexors and dorsiflexors using NMES. In the proposed system, the contractions were performed against exterior resistance, and the angle of the ankle joints was used as the control input to the video game. To test the practicality of the proposed system, an individual with chronic complete spinal cord injury (SCI) participated in the study. The system provided a progressive overload for the trained muscles, which is a prerequisite for successful muscle training. The participant indicated that he enjoyed the video game-based training and that he would like to continue the treatment. The results show that the training resulted in a significant improvement of the strength and endurance of the paralyzed lower leg muscles, and in an increased ROM of the ankle joints. Video game-based training programs might be effective in motivating participants to train more frequently and adhere to otherwise tedious training protocols. It is expected that such training will not only improve the properties of their muscles, but also decrease the severity and frequency of secondary complications that result from SCI.

Keywords — active gaming; muscle atrophy; muscle training; neuromuscular electrical stimulation; spinal cord injury; virtual rehabilitation; visual feedback.

Introduction

Reduction or absence of skeletal muscle function has been described as one of the most significant problems impacting the health and quality of life of persons with spinal cord injury (SCI) [1]. Pressure sores [2], low impact fractures [3], and deep venous thrombosis [4] are thought to be at least partially related to musculoskeletal atrophy and disuse in these individuals.

It is well established that electrical stimulation training can counteract musculoskeletal atrophy in individuals with SCI and, thus, decrease the likelihood of secondary complications and ultimately reduce costs associated with caregiving [1]. Although the benefits of electrical stimulation with respect to general health and strength have been documented in the literature for decades [1, 5-8], the optimal stimulation protocol for recovery of muscle strength and endurance has not yet been established. It is known, however, that loading of the extremities during neuromuscular electrical stimulation (NMES)-assisted contractions is effective in increasing muscle strength [9]. Additionally, it has been demonstrated that training with isotonic contractions results in a smaller risk of bone fracture [9] and increased blood circulation [10, 11] in comparison with isometric contractions. Furthermore, it has been emphasized that the amount of stress delivered to paralyzed tissue should meet a threshold consistent with overload and/or endurance training principles to make the training effective [6, 12].

A critical issue with current rehabilitative approaches lies in maintaining the participants' interest in performing repetitive training tasks and in ensuring their continued motivation to complete the training, especially during home-based treatment programs. It has been shown, that the use of rewarding activities and entertaining environments can substantially improve people’s motivation to practice and result in better training outcomes [13-16]. Moreover, with participants’ compliance is difficult to quantify, limiting ultimate conclusions that should follow long-term studies [6]. Besides, ensuring that proper training principles are followed generally requires the continuous participation and supervision of skilled medical or technical staff. These characteristics therefore provide a strong rationale for the development of training systems that are (1) effective, (2) attractive to individuals with SCI, and (3) easy to operate with minimal supervision.

Recent advances in technology have resulted in the availability of video games and virtual reality that have the capability to be used in rehabilitation [14, 17]. For example, video games were used by O’Connor et al. [14] in an attempt to increase the physiological responses of people with SCI using manual wheelchairs, and to examine the games’ effect on their motivation. The observations revealed that 87 % of the participants found that the games motivated them to perform their exercises [14]. Additionally, the motivational benefits of game-based exercises with visual feedback [13] and virtual reality [15] were observed during sitting balance training in individuals with SCI. The results of these studies demonstrate that the interactive gaming environment can motivate participants to practice dynamic movement tasks. Moreover, it can provide the patients and therapists with instantaneous feedback about performance and goal attainment during the training [13, 15].

Based on these considerations, we proposed a video game-based training system that is designed to integrate NMES and visual feedback therapy as a means to regain functional properties such as strength and endurance of the lower leg muscles as well as the range of motion of the ankle joints. The purpose of the present study was to evaluate the concept of the new training system using the following criteria: (1) the NMES training protocol must include isotonic contractions against exterior resistance; (2) the system must include an entertaining component which should be tied to the exercise challenge and guide the user through the protocol; and (3) the system must be easy to control and operate and require minimal supervision of medical or technical staff.

Methods

The training system consisted of a dynamic ankle joint training device, a tilt sensor, an electrical stimulator, a joystick, and a video game-based visual feedback training software program (Figs. 1 and 2). The participant was actively involved in the training procedure by operating the video game via NMES-induced ankle joint motions (Fig. 1). Specifically, the participant was required to continually adjust the level of electrical stimulation delivered to his plantarflexors (PF) or dorsiflexors (DF) using the joystick connected to the stimulator. The applied electrical stimulation evoked corresponding muscle contractions that controlled the video game through the resulting changes in ankle joint angular displacement (Fig. 1).

Dynamic ankle joint training device

During the training, the participant was seated on a padded bench with a backrest support. The position of the hip and knee joints were set to 90º of flexion, and the feet were firmly strapped to the foot platform (Fig. 2a). The platform was attached to the main shaft of the training device (Fig. 2b), which was inserted in the side bearings allowing smooth rotation (Fig. 2c). The axis of rotation of the main shaft was aligned with that of the ankle joints. The main shaft was composed of two sections, one of which supported the foot plate, and the other held the inverted pendulum. The inverted pendulum itself was 1m in length and was held in the upright position by the notch in the main shaft.

The inverted pendulum was used to provide resistance during the training exercise. Various weights could be added to or removed from the inverted pendulum in accordance with the strength of the participant. During the game-based exercise, the weight on the pendulum was 3 kg. The neutral position of the ankle joints (0º dorsiflexion/plantarflexion) corresponded to 4° of backward inclination of the inverted pendulum. Equivalent to the natural upright standing dynamics, this position created a higher load on PF than on DF. To prevent excessive joint movements during the training exercise, the range of angular displacements of the foot platform was mechanically restricted for safety consideration within the range of 30° plantarflexion and 20° dorsiflexion. The stoppers were covered by softer materials to absorb potential mechanical shocks when the platform stopped moving. The reaction torque sensor (TS11-200, Durham Instruments, Germany) with a capacity of 200 Nm, a sensitivity of 0.91 mV/V, and an excitation voltage of 18 V was mounted to the main shaft to measure the torque produced during the training exercise.

Tilt sensor

Tilt of the foot platform in the frontal plane was registered by a differential capacitance~~,~~ accelerometer- inclinometer with a range of ±2.0 g and a sensitivity of 660 mV/g (KXM52-1050, Kionix Inc., USA), which was securely attached to the rotating platform between the left and right foot (Fig.2b). The sensor signals were calibrated and processed to measure tilt of the platform. Signals were sampled using a 12-bit resolution data acquisition system (USB-6008, National Instruments, USA). Real-time data acquisition, processing, visualization, and storage were performed using the LabVIEW 8.5 software package (National Instruments, USA). The calculated tilt was used as the real-time control input to the video game.

Neuromuscular electrical stimulation

A programmable 4-channel neuromuscular electrical stimulator (Compex Motion, Compex SA, Switzerland) was used to deliver transcutaneous electrical stimulation to the ankle joint muscles. Two pairs of self-adhesive gel electrodes (ValuTrode, Denmark) were placed over the motor points on proximal (active electrode) and distal (reference electrode) ends of the triceps surae and tibialis anterior muscles of each leg, i.e., the surface of PF and DF, respectively. The 9 x 5cm electrodes were placed on the PF and 5 x 5cm electrodes were placed on the DF. The motor points were located approximately 12 cm below the knee joint, and the reference electrodes were placed 20 cm distally from the active electrode. NMES applied to PF generated an ankle torque that caused a forward rotation of the ankle joints, whereas NMES applied to DF resulted in a backward rotation of the ankle joints.

The stimulation current had a rectangular, biphasic, monopolar pulse waveform with a pulse duration of 300 μs, and the stimulation was delivered with a frequency of 40 Hz [18, 19]. The maximal amplitude (intensity) of the stimulation was set to 80 % of the intensity required to produce maximal torque. The range of the NMES intensity was determined prior to the training exercise and was based on the muscles' motor threshold (lower limit) and 80 % of the intensity required for maximum torque elicitation (upper limit). For the individual in this study, the stimulation ranged from 30 to 80 mA and from 20 to 60 mA for PF and DF, respectively.

Joystick

The stimulation intensity was controlled by the participant in response to the video game scenario using an analog joystick controller. A forward inclination of the joystick, which was connected to the electrical stimulator through an analog input port, resulted in stimulation of PF, whereas a backward inclination resulted in stimulation of DF. The intensity of the stimulation increased linearly with joystick motion.

Game-based exercise

The goal of the game was to navigate a moving “snake” around the screen in an attempt to hit randomly appearing targets (Fig. 3). The turning radius of the “snake” was controlled by the position of the ankle joints detected by the tilt sensor. Although only one type of ankle joint motion was used (i.e., plantarflexion and dorsiflexion in the frontal plane), the video game utilized three types of motion: with the joints in neutral position, the “snake” moved in a straight line; in order to produce clockwise or counterclockwise turns of the “snake”, the participant had to elicit plantarflexions (forward inclination of joystick) or dorsiflexions (backward inclination of joystick), respectively.

Visual feedback was provided by a large LCD monitor placed at eye level about 1.5 meters in front of the participant. To motivate the participant to improve his performance, a score representing the number of collected targets was displayed. With an increased number of collected targets, the “snake” increased its length. The trial was restarted every time the snake crossed the borders of the screen (‘out of bounds’). The game parameters were adjustable, namely, the speed of the snake and the number of targets, as well as the neutral position in the ankle joints and the sensitivity of the tilt sensor to the angular displacement of the foot platform. In addition, the amount of additional weights added to the pendulum varied the resistive force (torque) during movements of the ankle joint. For the purpose of this study, the parameters were set by the researcher.

The training was performed three days per week for a total of forty eight sessions. Each session lasted up to 60 minutes with a total time of the NMES of at least 45 minutes. The study was performed at the Toronto Rehabilitation Institute. A researcher assisted the initial setup (i.e., electrode placement and game parameters) prior to each training session. During the training, the participant was focused on the game the most of the time, and did not interfere with the researcher.

Outcome measurements

The following parameters were recorded during the 1st, 25th, and 48th training sessions: (a) the NMES intensity and (b) the duration of stimulation intervals for each muscle group, (b) the overall torque representing resultant torque exerted by the stimulated muscles and passive torque produced by the training device, and (c) the angular displacement of the foot platform (corresponding to ankle joint position). All data were sampled at 500 Hz and stored on a personal computer for subsequent analysis. The signals were low-pass filtered using a fourth-order, zero phase-lag Butterworth filter with the cut-off frequency of 5 Hz [20]. In addition to the aforementioned recordings, an open-question interview was carried out to assess motivational aspects of the training and to capture the participant's opinion on how the training system could be improved [13-15].

Participant

The male participant was 57 years old and has sustained chronic SCI (T3-T4) four years prior to taking part in this study. The participant's lesion completeness was classified as AIS A (American Spinal Injury Association Impairment Scale classification A). At the time of initial assessment, the participant demonstrated complete motor and sensory loss below the T4 level. He had experience using NMES of calf and thigh muscles in different research programs for about six months prior to our study. The participant did not experience spasticity and did not take medications for treatment or prevention spastic movement disorders. His personal treatment goals were to prevent secondary complications associated with impaired blood circulation and bone demineralization, and to improve his muscle mass in order to be able to participate in rehabilitation programs that use NMES. The participant gave written informed consent to the experimental procedure, which was approved by the local institutional ethics committee in accordance with the declaration of Helsinki on the use of human subjects in experiments.

Data processing and analysis

To analyze the data, we divided the acquired data into intervals of 3 min each. Thus, during a single session of 45 min long there were fifteen time intervals identified. A two-way ANOVA with repeated measures ($\alpha = 0.05$) along with a subsequent Tukey post-hoc test was applied to identify significant differences in recorded parameters throughout each training session and in comparison with the 1st training session. Results of the pooled data are presented as mean values and standard deviations (SD).

Results

Fig. 4 shows an example of one cycle of the exercise from plantarflexion to dorsiflexion and back to plantarflexion. Two kinds of muscle activities were utilized: First, isotonic concentric contractions occurred during rotation of the foot platform from plantarflexion to dorsiflexion and vice versa. The maximal torque values were exerted when the pendulum was moved away from its outermost position towards the upright position. As the angle in the ankle joints approached the neutral position, the magnitude of the torque decreased due to the fact that the inverted pendulum approached the upright position. After the pendulum reached the vertical point, it continued to move under its own weight until the foot platform reached the opposite outermost position (i.e., dorsiflexion or plantarflexion). Second, while the foot platform was kept in its outermost position, the participant continued to apply stimulation, which resulted in isometric contractions until a rotation in the opposite direction was required by the game. However, as seen in Fig. 4 even though the participant continued to generate isometric contraction the overall torque occurred in the opposite direction to the muscle contraction due to passive joint stiffness. That is, the torque generated by the joint stiffness was greater than the torque generated by the shortened muscle to which NMES was applied.

Note that during the 1st training session, the NMES resulted in effective muscle contractions only during the first 20 min. Then, due to developed muscle fatigue, the stimulation no longer produced torque sufficient to move the pendulum even with increased time intervals between the rotations of the foot platform. The game score representing the overall number of collected targets during the 1st session reached 12 points. However, from session to session the duration of the stimulation with effective muscle contractions increased reaching the required 45 min by the 20th session. The game score increased throughout the training period, reaching 421 points by the 48th session.

Fig. 5 depicts the change of the intensity of NMES (Fig. 5a) and duration of stimulation intervals for each muscle group (Fig. 5b), the peak torque (Fig. 5c), and the angular displacement of the foot platform (Fig. 5d) over time during the 1st, 25th, and 48th training sessions. The values of the stimulation intensity did not change significantly throughout the training period, reaching 80.0 mA during stimulation of PF and 60.0 mA during stimulation of DF (Fig. 5a). The duration of NMES of PF during the 1st training session significantly increased from 6.3 ± 1.3 s (0-3 min of the training session) to 8.5 ± 2.5 s (18-20 min of the training session). During stimulation of DF, the duration of NMES was increased from 5.6 ± 0.9 s (0-3 min of the training session) to 7.9 ± 1.5 s (18-20 min of the training session). There were no significant changes in the duration of NMES throughout the 25th and 48th training sessions: during stimulation of PF the average values reached 5.7 ± 1.3 s and 5.7 ± 1.5 s, respectively; during stimulation of DF the average duration of NMES reached 5.3 ± 0.8 s and 5.4 ± 1.6 s, respectively (Fig. 5b).

The torque varied from 11.0 ± 1.7 Nm to 10.4 ± 0.7 Nm during plantarflexion, and from -5.1 ± 0.8 Nm to -4.1 ± 0.4 Nm during dorsiflexion during the 1st training session. In the 25th session the torque values significantly increased during both plantarflexion and dorsiflexion reaching 23.9 ± 3.6 Nm and -10.0 ± 0.9 Nm, respectively, during the first 3 min of the session. However, at the end of the training session the torque values dropped to 10.0 ± 1.0 Nm and -6.0 ± 0.4 Nm, respectively. During the 48th training session, the torque values reached 27.0 ± 4.0 Nm during plantarflexion and -16.0 ± 2.0 Nm during dorsiflexion during the first 3 min of the session. At the end of the session, the torque values decreased to 11.1 ± 1.1 Nm and -10.8 ± 1.0 Nm, respectively (Fig. 5c).

The range of motion (ROM) of the ankle joints defined prior to the training period by passive plantarflexion and dorsiflexion varied within the range of 30° and -20°, respectively. However, during the muscle contractions imposed by NMES, the ROM was lower and varied during the 1st training session from 17.7 ± 2.1º to 16.6 ± 1.0º during plantarflexion, and from -2.9 ± 0.8º to -2.7 ± 0.3º during dorsiflexion. During the 25th training session, the ROM significantly increased reaching 25.1 ± 3.2º during plantarflexion and -12.0 ± 1.1º during dorsiflexion during the first 3 min of the session, and 22.9 ± 0.9º and -2.2 ± 0.4º, respectively during the last 3 min of the session. In the 48th training session, the ROM was higher reaching 28.7 ± 3.4º and -17.9 ± 1.5º during the first 3 min of the session during plantarflexion and dorsiflexion, respectively. At the end of the training session the ROM decreased to 25.5 ± 0.8º and -3.9 ± 0.3º, respectively, which was still significantly higher in comparison with the values during the 1st training session (Fig. 5d).

During the interview, the participant reported that he enjoyed controlling the video game-based training. He stated that the video game was challenging to play, but could be easily adjusted to meet the needs of the participant. The participant also reported that the instruction to maximize his score during each trial motivated him to play and to keep his attention on the game throughout the whole session. The participant was encouraged to participate in this training program on a regular basis.

Discussion

We developed a new training system that integrates NMES and visual feedback. We demonstrated that the protocol used in this study yielded significant training effects on the strength and endurance of the paralyzed lower leg muscles, as seen through increased torque values and training session duration, and improved the range of motion of the ankle joints. There was greatest improvement over the first few training sessions as seen in the results between the 1st and 25th training sessions. As opposed to existing training programs, our approach incorporated isotonic concentric contractions against different levels of resistance, included an entertaining component, and required minimal supervision of medical or technical staff.

To the best of our knowledge, there is no conventional protocol or device aimed at regaining calf muscle properties in individuals with SCI. Most of the existing NMES-training paradigms include stimulation of three main muscle groups: the quadriceps, hamstrings, and gluteal muscles [1, 21-24]. Thus, the function of the *calf muscles* and *ankle joints* often remain unaffected. Existing protocols of lower leg muscles' NMES-training in populations with SCI include stimulation during isometric contractions, i.e., with a constant muscle length and fixed ankle joints [6, 25]. It has been demonstrated that isometric contractions induce higher forces than concentric contractions [10], thus, more likely causing muscle hypertrophy [6, 26]. Such conditions introduce a higher risk of bone fracture [9], decreased blood circulation [10, 11], and decreased ankle joint mobility. We therefore suggested a system that includes dynamic plantarflexion and dorsiflexion movements against different levels of resistance, and thus, decreases the probability of the aforementioned risks. To eliminate the risk of excessive and unsafe motions in the ankle joints during the training, our system was secured with mechanical stoppers which ensured a safe rotation of the foot platform within any individual’s range of motion. Isometric contractions also took place when the foot platform was maintained at the outermost plantarflexion or dorsiflexion positions. However, the torque values produced were relatively low because the electrical stimulation was applied to shortened muscles, thus making the stimulation in this condition safe.

Although the game parameters (speed of the snake, the number of targets, and sensitivity of the tilt sensor) and the amount of additional weights added to the pendulum were adjustable, the current training protocol employed the settings which stayed unchanged throughout all training sessions. However, the exercise challenge (i.e., motivation to get a higher score) guided the participant through the protocol, thus, providing an overload for the muscles during the training.

We believe that the stress induced by the current protocol resulted in an increment of the muscle strength, and, thus, increased torque which remained elevated throughout the training period. For example, the torque during dorsiflexion almost quadrupled by the end of the training period in comparison with the initial values. Additionally, the duration of the training sessions significantly increased indicating the improvement in the endurance. Moreover, the ROM in the angular joints was also significantly increased during NMES-imposed muscle contractions.

The goal of our game-based exercise required that the participant stimulates his muscles in an intermittent manner, otherwise, the “snake” would not move purposefully around the screen. Instead, it would rotate around a small circle if the ankle position was maintained in plantarflexion or dorsiflexion, or move straight out of bounds if the ankle position was maintained at neutral position. Thus, the stimulation consisted of alternating cycles of activity and rest of about the same duration in each muscle group. It has been shown that a combination of 50% work and 50 % rest can produce a much greater gain in strength and endurance than other work-rest ratios during electrical stimulation as it provides optimal accumulation of metabolites and depletion of energy to stimulate hypertrophy and training of muscles [11]. Thus, this pattern of stimulation provided both the optimal work-rest ratio and effective muscle performance throughout the training session.

At the same time, the values of the torque and the ROM decreased by the end of each training session, thus, revealing signs of muscle fatigue. Interestingly, the reduction of the ROM was less pronounced during plantarflexion and more prominent during dorsiflexion. It might be linked with a shortening of PF and thus, with a changed equilibrium position of the ankle as it has been shown that altered ratios of agonists' and antagonists' length in the ankle joint is often occurring in individuals with SCI [25]. On the other hand, it might be associated with a more pronounced atrophy in DF prior to the training, and/or a difference in muscle composition between PF and DF with predominance of faster fatiguable muscle fibers in DF [6, 26, 27]. As such, because the current training protocol provided an equal load to both muscle groups, the muscle fatigue developed in DF faster. Nevertheless, we believe that the resistance to muscle fatigue, and as a consequence, the higher values of the torque and ROM at the end of the training session, could be improved with continuation of this training program.

Another key observation resulting from this study was that the interactive gaming NMES intervention can motivate a person with chronic SCI to perform muscle training exercises. Our participant indicated that he enjoyed the video game-based tool, and that he would like to continue the treatment. It is suggested that the positive responses to the experience as well as the expressions of interest in having additional sessions with the system reflect high motivation of participants for therapy [15]. It has been noted earlier that a regular training program might not be available or might be too difficult to participate in, either physically and/or psychologically [14]. Our approach was applied to an individual with complete SCI, and thus, with severe impairment of leg muscle function. However, the system parameters could have been changed permitting the participant to successfully train even with progressively increasing fatigue. Moreover, characteristics of the system would allow individuals with even less preserved motor function (i.e., with weaker muscles and/or with narrower ROM in the ankle joints) to participate in this training program.

Additionally, the system setup and applied protocol required minimal supervision from medical or research staff: once the game parameters, range of motion, and the level of resistance were set, the participant was able to perform the training without any further assistance.

Limitations and future directions

Although the proposed training system included isotonic plantarflexions and dorsiflexions, their role in the training in comparison with isometric contractions was relatively small. Despite the fact that the values of the torque were the largest during isotonic contractions and the lowest during isometric contractions, thus, making the training parameters safe, there is a need in developing a system which would include a more prominent and continuous isotonic component. It is preferable to have a larger variety of entertaining video games targeted to different populations (i.e., dependent on disorder, age, and/or interest). In addition, algorithms for automatic modification of the game parameters according to participant's performance could be added to the training protocol. Further research along with a randomized control study might be required to investigate and compare the motivation level and to what extent muscle function might be enhanced using our system and other rehabilitation approaches.

Conclusion

In our case study, the proposed video game-based training that integrates NMES and visual feedback successfully motivated the participant and resulted in significant training effects on the strength and endurance of the paralyzed lower leg muscles as well as improved the range of motion of the ankle joints. The system provided a progressive overload for the trained muscles, which is a prerequisite for successful muscle training. Video game-based training programs must be effective in motivating participants to train more frequently and adhere to otherwise tedious training protocols. It is expected that such training will not only improve the properties of their muscles, but also decrease the severity and frequency of secondary complications that result from SCI. In addition, the improvement in muscle strength may be instrumental in helping individuals with incomplete SCI to increase their participation in other rehabilitation programs and activities designed to improve function.

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Conflict of interest statement

The authors declare no conflict of interest.

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Figure Legends

Figure 1. Schematic diagram of the main components and sequence of action of the training system.

Figure 2. Dynamic ankle joint training device: (a) an overall view of the foot platform with the inverted pendulum locked in place at the end of the main shaft, and a participant on a padded bench using the system; (b) foot platform with tilt sensor, main shaft with torque sensor, and notch for the pendulum (the pendulum is not shown); (c) static components of the system: base plate, bearings, and stoppers. Drawing is not to scale.

Figure 3. Interface of game-based exercise. Shown are "snake", targets, score, and adjustable parameters which include: speed of snake, number of targets, adjustment of neutral position of ankle joints, and range of motion (i.e., maximal plantarflexion and dorsiflexion).

Figure 4. Example of one cycle of the exercise recorded during the second minute of the 1st training session: transition from plantarflexion to dorsiflexion and back to plantarflexion. (a) NMES intensity; (b) torque (bold black line) and angular displacement (bold gray line). Periods of isotonic concentric contractions are shown by gray color. Scale for the torque is shown on the left; scale for the angular displacement is shown on the right.

Figure 5. Pooled data showing the parameters recorded during the training session: (a) intensity and (b) duration of stimulation intervals for each muscle group, (c) torque, and (d) angular displacement of the foot platform over time during the 1st, 25th, and 48th training sessions. Positive values represent parameters during plantarflexion; negative values represent parameters during dorsiflexion. Asterisks indicate statistically significant differences in comparison with the 1st training session (* $P < 0.05$).