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Hemodynamics of Active Ankle Motion in a Seated Position Using a Soft Robotic Wearable Actuator: A Comparative Study of Exercise Protocols and Cycles

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***Abstract*— This study evaluates a soft robotic wearable device, equipped with a Hyper-extension Pneumatic Actuator (HPA), to prevent deep vein thrombosis (DVT). We investigate the hemodynamic efficacy of a novel "Combined" exercise protocol, which strategically integrates the high-load advantage of resistance exercise with the wide range of motion from induced exercise, all delivered by a single soft actuator system. The effects of four distinct exercise modalities on key hemodynamic parameters, including time-averaged maximum blood flow velocity (TAMAX), were systematically evaluated in healthy participants. Results demonstrated that all active exercise modalities showed a strong tendency to augment blood flow velocity compared to rest (effect size r>0.8). Notably, the "Combined" protocol yielded a statistically significant increase in TAMAX compared to exercise without the device ($p < .05$). This enhancement is attributed to the protocol's ability to elicit high-quality, high-tension muscle contractions by balancing exercise load with a sufficient range of motion, thereby optimizing the muscle pump mechanism. These findings provide engineering guidelines for developing effective DVT prevention strategies, demonstrating that the intelligent integration of a control protocol—not just the hardware alone—is key to maximizing hemodynamic efficacy.**

I. Introduction

Prolonged seated postures are a prevalent condition experienced by many individuals in various situations, including air travel, desk work, and particularly during extended periods of immobilization in postoperative recovery. Under such conditions, blood flow in the lower limbs can stagnate significantly, elevating the risk of developing deep vein thrombosis (DVT) [1-3]. If a thrombus dislodges and obstructs a pulmonary artery, it can lead to a life-threatening pulmonary thromboembolism. As clinical symptoms are often minimal or absent, early prevention is paramount [4,5]. The most effective countermeasure against this venous stasis is the activation of the "muscle pump," a physiological mechanism wherein the rhythmic contraction and relaxation of the calf muscles propel venous blood back toward the heart [6]. In clinical settings, it is well-established that passive or active assisted exercise, where a physical therapist manually mobilizes a patient's ankle joint, is effective in promoting this muscle pump action [6].

To engineer a solution that replicates this manual approach, various exercise-assisting devices have been developed [7-15]. However, a significant portion of these are motor-driven passive motion devices that are often insufficient in eliciting the user's active muscle engagement. Furthermore, most devices with more advanced functions are rigid exoskeleton robots constructed from metallic frames. While capable of delivering substantial assistive forces, they are often hindered by drawbacks such as excessive weight, bulk, poor wearability, and discomfort from joint misalignment [7-12]. In contrast, the soft robotic wearable device utilized in this study features an design that integrates the human skeleton into its kinematic linkage mechanism [13-15], thereby effectively reducing mechanical stress on the joints and ensuring a high degree of safety without necessitating complex control [16].

However, the mechanical structure alone is insufficient; the control strategy (exercise protocol) is crucial for maximizing the muscle pump effect. Previous research has indicated that resistance exercise, which generates strong muscle contractions, is effective for promoting blood flow [17], while induced exercise, characterized by a wide range of motion, is also considered vital for promoting muscle relaxation [18]. We have previously evaluated the effects of resistance and induced exercises on blood flow in a supine position using a similar soft robotic device [19]. However, an evaluation in a seated posture—a position more common in daily activities and associated with a heightened DVT risk—and the efficacy of a combined protocol that integrates the advantages of both modalities have not been systematically investigated. Therefore, to address this research gap, this study proposes a novel combined exercise (Combine) protocol designed to maximize the muscle pump effect. We hypothesized that achieving both the high muscle activation imparted by resistance exercise and the extensive range of motion afforded by induced exercise would yield a synergistic improvement in blood flow that surpasses that of any single exercise mode. Additionally, while the timing of muscle contraction and relaxation is critical for exercise efficiency [20], the optimal exercise cycle has yet to be determined.

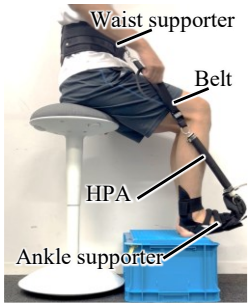

Figure 1. DVT prevention device in seated posture.

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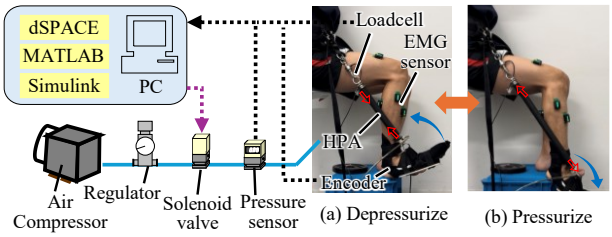


Figure 2. System components with HPA.

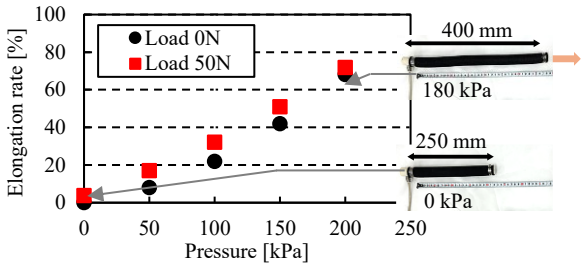


Figure 3. Elongation rate of HPA [20]. This illustrates the equilibrium elongation achieved at a constant external load.

The purpose of this investigation is to experimentally validate our hypothesis in a seated posture. To this end, we employed a soft robotic wearable device to conduct a comprehensive analysis of the effects of four exercise modalities and two exercise cycles on blood flow velocity, muscle activity, joint range of motion, and device-generated tension in healthy young adults.

The main contributions of this study are as follows:

- Establishing the technological foundation for a soft robotic device that achieves multiple exercise modes with a single actuator.
- Experimentally demonstrating, as a fundamental study for DVT prevention, that a combined exercise protocol integrating resistance and induction is the most effective protocol, surpassing other single-mode approaches.

II. DVT Prevention Device

This section provides an overview of the DVT prevention device, details the characteristics of its Hyper-extension Pneumatic Actuator (HPA), and introduces the newly proposed combined exercise protocol.

A. Device Overview

The soft robotic wearable device used in this investigation is an evolution of a prototype developed in prior research [19-21]. As illustrated in Fig. 1, the core component of the device is a flexible Hyper-extension Pneumatic Actuator (HPA). The system is built upon a unique design philosophy that incorporates the human skeleton as an integral part of its linkage mechanism. This configuration substantially reduces mechanical stress on the joints and offers inherent backdrivability, which ensures high safety without requiring sophisticated control systems. The device comprises supporters worn at the user's waist and ankle, a length-adjustable belt, and the HPA that connects these two points.

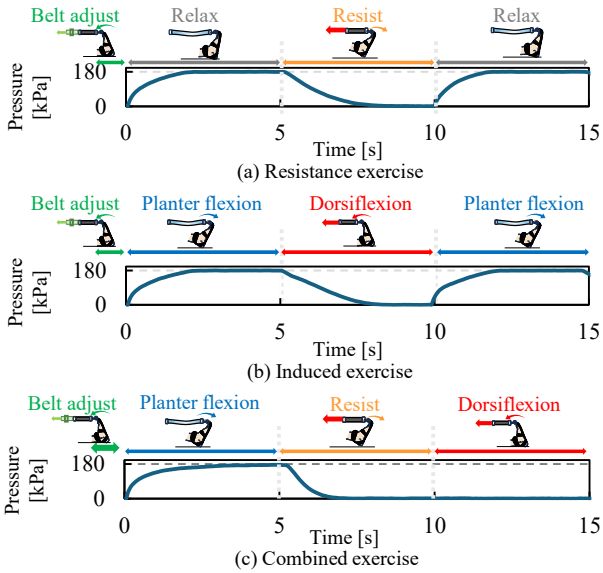


Figure 4. Proposed exercise protocols with the device. The figure shows the long cycle protocols as an example: (a) Resistance exercise (10s/cycle), (b) Induced exercise (10s/cycle), and (c) Combined exercise (15s/cycle).

Device operation is governed by a real-time control system (MicroLabBox, dSPACE GmbH), as depicted in Fig. 2. This system precisely actuates the HPA to apply loads for active motion (resistance exercise), guide movements (induced exercise), and execute the integrated combined exercise protocol detailed below.

B. Hyper-extension Pneumatic Actuator

The characteristics of the HPA used in this device, obtained by applying static axial loads as detailed in our prior work [20], are shown in Fig. 3. The HPA is constructed from rubber reinforced with a composite of long threads and short-oriented fibers, allowing it to elongate significantly in the axial direction with negligible radial expansion upon pressurization [22]. This property provides sufficient elastic force for ankle motion. The maximum applied air pressure (180 kPa) and resulting elongation (60%) were determined to be sufficient for generating the required resistive forces and range of motion for effective ankle exercise in our prior work [19-21]. This HPA not only provides adequate elastic force for ankle exercise but also offers a larger strain and a smaller radial expansion rate than McKibben-type [23] or other elongating artificial muscles [24]. This small radial expansion prevents impediment to the device's operation and uncomfortable contact with the user's leg during actuation. The HPA used in this device has a total length of 250 mm, an outer diameter of 32 mm, an inner diameter of 28 mm, and a weight of 0.04 kg.

C. Proposed Combined Exercise Protocols

To experimentally test the central hypothesis of this study, the device's control system was programmed to deliver single-modality exercises as well as an integrated combined exercise. The specifics of each evaluated protocol are outlined below.

1) *Resistance Exercise:* As depicted in Fig. 4(a), this protocol begins with the experimenter adjusting the belt length and positioning the subject's ankle at their

comfortable maximum dorsiflexion angle. Upon HPA inflation, the ankle moves to a relaxed angle. The user then performs plantar flexion against the elastic restoring force of the deflating HPA. This cycle of relaxation during inflation and active resistance during deflation facilitates continuous, loaded ankle joint motion.

2) *Induced Exercise:* Illustrated in Fig. 4(b), the initial setup for this protocol mirrors that of the resistance exercise. The user synchronizes their ankle movement with the device, moving into plantar flexion as the HPA elongates (pressurizes) and into dorsiflexion as it contracts (depressurizes). This induced modality is designed to facilitate smooth ankle articulation across a wide range of motion.

3) *Combined Exercise:* This integrated protocol, shown in Fig. 4(c), also shares the same initial setup. The user first moves into plantar flexion in coordination with HPA elongation (plantar flexion induced phase). During the subsequent deflation, as the HPA generates elastic force, the user actively resists this force (resistance phase). Finally, the user moves into dorsiflexion in coordination with HPA contraction (dorsiflexion induced phase). The combined protocol therefore sequentially executes three distinct phases: plantar flexion induction, resistance, and dorsiflexion induction.

III. Experimental Evaluation of Blood Flow during Combined Exercise

The primary objective of this experiment was to elucidate the effect of the proposed combined exercise protocol on lower limb hemodynamics in a seated posture and to benchmark its efficacy against other active exercise modalities.

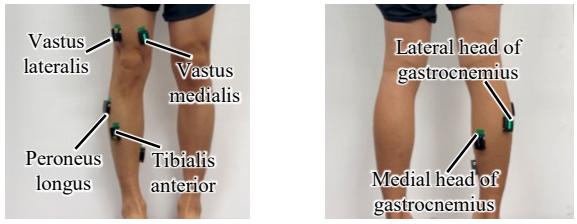
A. Methods

9 healthy young male subjects (height: 168.9 ± 5.3 cm) participated in this investigation. The study protocol was formally approved by the Institutional Ethics Committee of Chuo University (Approval No. 2024-125). All participants remained in a stable seated position for the duration of the experiment. Each participant was fitted with the device on their right lower limb, as depicted in Fig. 2.

The experiment encompassed several conditions: a baseline resting state (Rest), active exercise performed without the device (No device), resistance exercise (Resist), and induced exercise (Induce). The latter three modalities were each performed at two cycle durations: a short cycle (6 s/cycle) and a long cycle (10 s/cycle). The newly proposed combined exercise (Combine) was also evaluated at two durations: a short cycle (9 s/cycle) and a long cycle (15 s/cycle). The short cycle for the combined protocol was composed of three sequential 3-second phases (induced plantar flexion, resistance, and induced dorsiflexion), while the long cycle consisted of 5-second phases. Each condition was maintained for a duration of 60 seconds, and the sequence of conditions was randomized for each participant. A sufficient recovery period was allocated between trials to ensure that hemodynamic parameters returned to their baseline resting values.

A dSPACE system (MicroLabBox, dSPACE GmbH) was utilized for device actuation and the synchronized acquisition of electromyography (EMG) and kinematic data. Blood flow velocity was measured independently via an ultrasound diagnostic imaging system (LOGIQ eV2VA, GE HealthCare). The time-averaged maximum blood flow velocity (TAMAX) within the right femoral vein was quantified by positioning the ultrasound probe on the thigh surface. To ensure measurement consistency, the initial probe location was marked and referenced for all subsequent measurements. Muscular activity was monitored using wireless surface EMG sensors (Trigno Avanti, DELSYS) affixed to six key lower limb muscles integral to ankle articulation (Fig. 5): the tibialis anterior, peroneus longus, medial and lateral heads of the gastrocnemius, and the vastus medialis and vastus lateralis. Ankle kinematic data (joint angle) were captured using an encoder (E6B2-CWZ6C, OMRON), and the tension generated by the HPA was recorded with a load cell (LUR-A-500N, KYOWA). For the analysis of blood flow velocity data, the TAMAX for each cardiac cycle was calculated from the recorded Doppler waveform. The average of these values over the 60-second measurement period was then used as the representative value for each experimental condition. For blood flow velocity data, the TAMAX for each heartbeat was calculated from the measured waveform, and the average value over the 60-second period was used as the representative value for each condition.

EMG data were first subjected to a 20–450 Hz band-pass filter and subsequently processed using a root mean square (RMS) calculation. These data were then normalized by the maximum voluntary contraction (MVC) value, predetermined for each muscle, and expressed as a percentage (%MVC). For the final evaluation metric, the 60-second data segment from each exercise condition was partitioned into cycles. The integral of the EMG signal for each cycle (iEMG) was computed using the trapezoidal rule. These values were then averaged and divided by the cycle duration to yield the mean muscle activity level (%MVC/sec). To derive a stable representation of the range of motion (ROM) and tension data while accounting for temporal variations such as motor adaptation and fatigue, the 60-second measurement period was divided into two 30-second halves. The ROM (defined as the difference between the maximum and minimum joint angles) and the maximum tension were calculated for each half and subsequently averaged to produce the final evaluation metrics. All statistical analyses were conducted using the R statistical software package (ver. 4.4.1).



(a) Front side (b) Back side

Figure 5. EMG sensor placement on lower limb muscles.

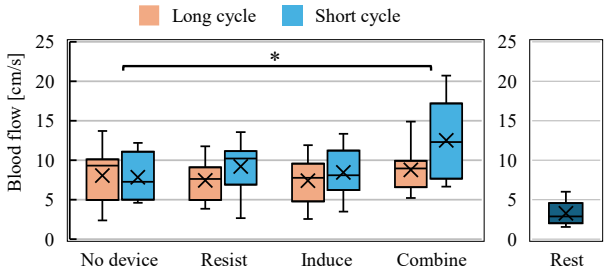


Figure 6. Time-averaged maximum blood flow velocity (TAMAX) under each exercise condition. *: $p < 0.05$, there was a non-significant except for the groups marked with *.

TABLE I JOINT ANGLES AND MAXIMUM FORCE IN EACH MOVEMENT PATTERN

Movement pattern	Cycle	Maximum angle [deg]	Minimum angle [deg]	ROM [deg]	Maximum force [N]
No device	Long	33.5 ± 10.3	-6.5 ± 3.1	40.0 ± 11.4	0.0
No device	Short	31.9 ± 12.6	-11.4 ± 7.1	43.3 ± 10.0	0.0
Resist	Long	34.3 ± 9.3	13.8 ± 4.4	20.5 ± 5.3	69.2 ± 15.5
Resist	Short	32.4 ± 7.0	11.5 ± 4.6	20.9 ± 3.6	74.6 ± 13.2
Induce	Long	30.3 ± 7.7	-4.1 ± 3.4	34.4 ± 9.8	26.2 ± 8.2
Induce	Short	27.6 ± 9.6	-3.7 ± 2.9	31.3 ± 10.0	28.3 ± 6.6
Combine	Long	32.5 ± 9.2	-3.0 ± 4.9	35.5 ± 9.0	76.7 ± 9.4
Combine	Short	38.0 ± 8.2	-1.3 ± 4.6	39.3 ± 8.2	83.5 ± 11.1

B. *Results*

All exercise modalities showed a strong tendency to increase blood flow velocity relative to the resting state (effect size $r>0.810$); however, following a Bonferroni correction for multiple comparisons, these differences did not reach statistical significance ($p>.05$). To meticulously examine the effects of the exercise modality and cycle duration, a two-way repeated-measures analysis of variance (ANOVA) with Aligned Rank Transform (ART) was performed. The analysis revealed statistically significant main effects for both exercise modality ($F(3,56) = 3.20$, $p=.030$) and exercise cycle ($F(1,56) = 6.20$, $p=.016$). The interaction between these two factors was not statistically significant ($p=.221$).

Fig. 6 presents boxplots of the TAMAX for each exercise condition, with the resting condition included for reference. As illustrated, the short cycle consistently tended to yield higher blood flow velocities than the long cycle. A post-hoc multiple comparison test (Tukey's method) among the exercise modalities revealed that the combined exercise (Combine), with a mean TAMAX of 16.8 cm/s, produced a statistically significant increase in blood flow velocity compared to the unassisted exercise (No device; 11.5 cm/s) ($p<.05$, $r=0.336$).

To elucidate the underlying mechanisms responsible for the observed hemodynamic differences, muscle activity and kinematic data were analyzed. A repeated-measures two-way ANOVA using ART, analogous to the blood flow analysis, was performed on the activity levels of each muscle. This analysis identified a significant main effect of exercise modality for all muscles investigated (all $p<.05$). Conversely, no significant main effect of the exercise cycle or any interaction effect was detected for any muscle.

Fig. 7 displays the mean muscle activity levels (%MVC) for the six lower limb muscles across each exercise modality. Post-hoc multiple comparison tests unveiled distinct activation patterns for each muscle. The activity of the tibialis anterior was maximal in the No device condition, exhibiting a significantly higher value than in the Resist condition specifically. For the peroneus longus and both heads of the gastrocnemius, the Combine condition tended to elicit high levels of activity. Specifically, for the peroneus longus, the activity during the Combine condition was statistically significantly higher than during the Resist condition. For the medial head of the gastrocnemius, the Combine condition demonstrated significantly greater activity than both the Induce condition ($p<.01$, $r=0.403$) and the No device condition ($p<.05$, $r=0.353$). A congruent activation pattern was observed in the quadriceps femoris (vastus medialis and lateralis). For both of these muscles, the Combine and Resist conditions induced significantly higher muscle activity levels than the Induce and No device conditions (all comparisons $p<.01$, $r>0.335$).

Table 1 summarizes the kinematic and kinetic data for each exercise modality. The ROM was greatest in the No device condition, averaging 40.0 ± 11.4 deg for the long cycle and 43.3 ± 10.0 deg for the short cycle. In contrast, ROM was attenuated in the three modalities involving the device, with the Resist condition exhibiting the most restricted movement. The ROM for the Combine and Induce conditions surpassed that of the Resist condition. Conversely, the maximum tension was remarkably high in both the Combine and Resist conditions. The Combine condition registered an average of 76.7 ± 9.4 N for the long cycle and 83.5 ± 11.1 N for the short cycle, while the Resist condition recorded 69.2 ± 15.5 N and 74.6 ± 13.2 N, respectively. These results suggest that the augmentation of blood flow velocity is more strongly associated with the tension exerted during the exercise than with the ROM. These findings also indicate that the Combine condition sustained a larger ROM than the Resist condition while generating comparably high maximum tension.

C. *Discussion*

This study was designed to test the hypothesis that a combined exercise protocol, which strategically balances the high-tension advantage of resistance exercise with the wide-ROM advantage of induced exercise, would yield a synergistic hemodynamic improvement superior to that of single-modality interventions.

The most critical finding of this research is that the combined exercise protocol demonstrated a statistically significant improvement in the primary outcome, TAMAX, when compared to unassisted exercise. This result provides direct support for our initial hypothesis from a hemodynamic perspective. In the subsequent discussion, we aim to elucidate the underlying mechanism through an integrated analysis of muscle activity, maximum tension, and range of motion.

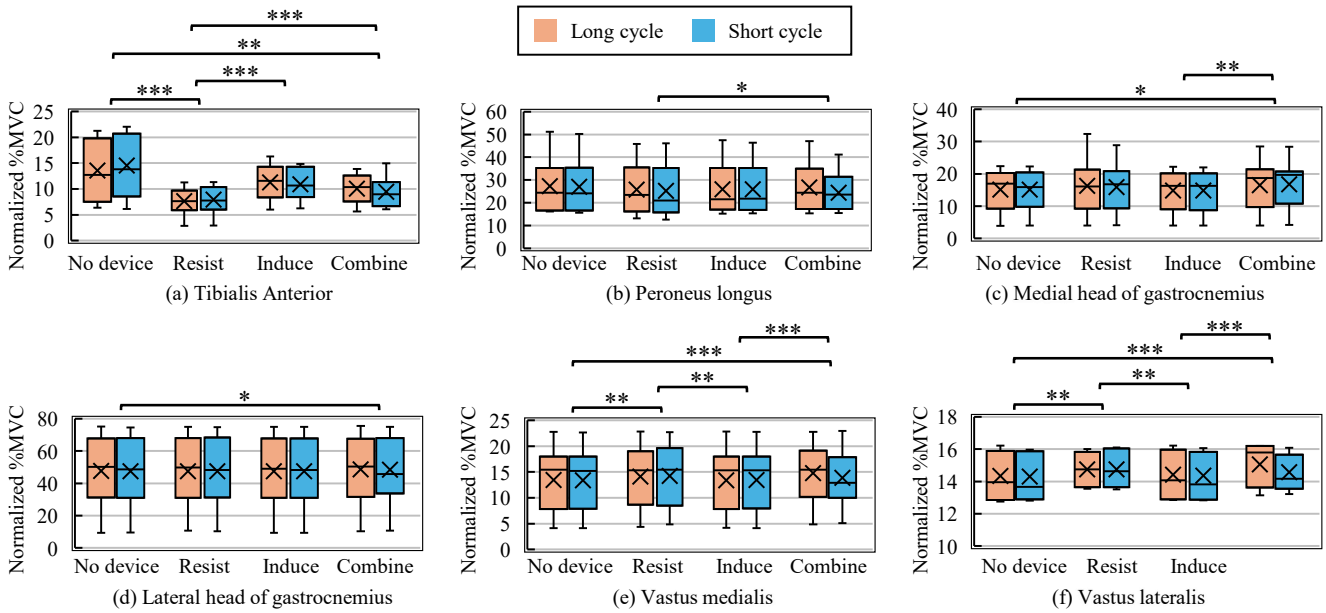


Figure 7. Average muscle activity levels of six lower limb muscles in each movement pattern. *: $p < 0.05$, there was a non-significant except for the groups marked with *.

First, our findings suggest that the magnitude of the motion itself is not the primary factor in the mechanism of blood flow improvement. In fact, a correlation analysis revealed no significant correlation between blood flow velocity and the maximum range of motion (ROM). On the other hand, the tension exerted during the exercise appears to be a more critical factor. However, this relationship is not a simple linear one; the correlation coefficient between the time-averaged maximum velocity (TAMAX) and the maximum tension was low ($\rho = 0.24$, $p < .05$). One potential reason for this weak correlation is the inter-subject variability in muscle activation. That is, even when the device applied high external tension, some participants may not have efficiently contracted the gastrocnemius muscle group, the prime mover for DVT prevention, resulting in insufficient activation of the muscle pump mechanism. This concept of "high-quality muscle contraction" is the source of the muscle pump action that efficiently propels venous blood toward the central circulation. This hypothesis is further supported by our analysis showing that the integrated electromyography (iEMG) of the gastrocnemius group was most active during the combined motion, which was the most effective intervention.

Furthermore, the combined motion tended to surpass the resistance motion in its blood flow-enhancing effect, despite the high tension produced by the latter. This difference is explained by the core of our hypothesis: the synergistic combination of benefits. Although previous studies have evaluated resistance and guided motions separately in a supine position [17, 18], our findings suggest that the efficacy of any single motion modality is limited, particularly in a seated posture where the risk of DVT is elevated. By incorporating elements of guided motion, the combined motion tended to achieve a greater range of motion (ROM) than resistance motion alone, while also generating the high tension necessary for a quality muscle contraction. In other words, the combined motion achieved the most effective balance of two factors essential for enhancing muscle pump efficiency within a single exercise cycle: a powerful contraction (high tension) followed by a sufficient ROM that promotes complete relaxation. Additionally, this study identified a significant main effect for the exercise cycle. The influence of movement velocity on blood flow has been previously reported for both passive exercise and active exercise without external load. This is consistent with the physiological principle that increasing the frequency of muscle pump activations per unit of time augments total blood flow. In the present study [25, 26], the superiority of the short cycle was observed across the ANOVA results as a whole. This suggests that as long as sufficient muscle contraction force (resist) and a stable range of motion (induction) are reasonably balanced, an increase in exercise frequency leads to an enhancement in blood flow.

IV. Conclusion

This study sought to identify the most effective exercise modality for DVT prevention in a seated position by comparing multiple ankle exercise protocols facilitated by a soft robotic wearable device. The experimental results statistically demonstrated that the combined exercise protocol, which integrates the high exercise load of resistance exercise with the wide range of motion from induced exercise, most effectively increased lower limb blood flow velocity compared to other single modalities. This superiority is attributed to the fact that the combined protocol maximized the muscle pump effect by achieving both a high exercise load and a sufficient range of motion, accompanied by high-quality muscle contraction. Furthermore, it was also clarified that shorter exercise cycles are more effective. These findings highlight the importance of an approach that intelligently integrates multiple functions, rather than pursuing a single function, in the development of exercise assistance devices for DVT prevention.

Several challenges remain for future work. First, since the participant cohort in this study was limited to healthy young men, future clinical evaluations should be conducted on populations at high risk for DVT, such as elderly individuals and postoperative patients, to verify the effectiveness and safety of this protocol. Second, assuming long-term application, it is also important to evaluate the effects of each exercise protocol on subjective perceptions of fatigue and comfort. In the future, we aim to develop more advanced control algorithms that can automatically optimize the exercise modality and cycle based on the user's physiological condition and therapeutic goals, leveraging the findings of this research. Third, although significant main effects were detected, the small sample size (n=9) necessitates larger, more diverse studies to enhance the statistical reliability of these findings.

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