A Cable-Driven Exosuit for Bidirectional Upper Limb Resistance Exercises

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***Abstract*—Recently, intensity-adjustability, interactivity, and multi-functionality have become crucial features of home fitness devices. To accommodate these features, there has been a demand for a new type of device, leading to the development of both passive and active cable-driven exosuits. These exosuits demonstrate features of intensity-adjustability and interactivity. However, there is further potential for development in terms of multi-functionality. This letter presents the development of a cable-driven exosuit for the upper limb home fitness capable of transmitting bidirectional resistance. In this exosuit, two types of cable routing were established for each direction of resistance. Due to the characteristic of cables transmitting force only by tension, these cable routings were designed to allow the increase in cable length, while enabling the appropriate direction in torque to be transmitted for various exercises. Additionally, routing anchors are designed to minimize the influence of friction in various postures. To enable resistance adjustment, a derail-preventing actuator with a force sensor has been applied. In the verification of the exosuit, muscle activation analysis was conducted on three healthy participants. We confirmed the activation of six upper limb muscles through various intensities and observed that the exosuit can alter muscle activation patterns differently from the resistive bands.**

***Index Terms*—Wearable robotics, cable-driven mechanism, exosuit.**

I. Introduction

IN RECENT years, there has been a growing interest in fitness as people have increasingly recognized the importance of maintaining an active and healthy lifestyle. Among this rising interest, advancements in technology and improved access to information have allowed people's fitness activities to become less limited by time and location. Additionally, recent pandemic situations like COVID-19 have resulted in a sharp increase in the demand for innovative types of home fitness [1]. This kind of increasing demand can be observed in the recent fitness trend. According to the recent survey, each of "Wearable Technology" and "Home exercise gyms" ranked first and second among the latest fitness keywords [2].

The increasing demand for fitness technology has led to the emergence of various home fitness devices for professional training. These devices include distinctive features that address the pain points of existing home fitness devices [3]. The main features of these devices are intensity-adjustability, interactivity, and multi-functionality. Intensity-adjustability enables the provision of personalized resistance that could enhance effectiveness of the exercise. Interactivity is the capability of integrating various devices and software with the system, providing continuous feedback based on exercise data to motivate the user [4]. Multi-functionality addresses the challenge of limited space in home settings by enabling various exercises to be performed with a single device.

A representative of a recently developed home fitness device is Tonal (TONAL Co., USA), which can appropriately adjust exercise intensity for users. However, this kind of device has limitations from both an interactivity perspective and a space efficiency perspective, despite being capable of automatic intensity adjustment. To accurately log user data, additional devices such as sensors attached to the body are required, and while they allow for various movements, they are relatively bulky and have limitations in performing movements in various directions. Therefore, there is a need for the development of a more appropriate type of device that can effectively utilize all of these features.

Wearable devices have potential as home fitness devices that are able to satisfy these features. To date, wearable devices have predominantly been developed with an emphasis on interactivity. Examples include smartwatches that can track user status [5] and devices integrated with gaming elements to enhance user motivation [6]. From the perspectives of intensity-adjustability and multi-functionality, it is necessary to develop wearable devices in forms that transmit force to the user's body such as

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wearable robot. Wearable robots that directly transmit force to the human body come in two types: exoskeletons and exosuits. In the case of exoskeleton types [7], [8], [9], rigid frame based mechanisms are able to transmit the bidirectional torque on the human joint effectively. In contrast, exosuits [10] are composed of soft materials, enabling the transmission of force through lightweight and simple mechanisms. Given the dynamic movement of fitness, exosuit type robots are more suitable. To assist with exercise, these robots need to transmit resistance, which is a different requirement from conventional exosuits. Despite this need, few attempts have been made to develop exosuits specifically designed for fitness.

A representative examples are the exosuits for home fitness previously developed by Park et al. [11], [12]. They developed both passive and active exosuits using BoA dial-based passive mechanisms and cable-driven active mechanisms, respectively. Through these actuation systems, they implemented a system for adjusting fitness exercise intensity through exosuits. Additionally, they demonstrated the advantages of exosuit-type devices in interactivity by integrating sensors such as IMUs. However, previous works have the limitation of only transmitting unidirectional resistance, which restricts the exercise to pushing movements. To accommodate various types of fitness activities, exosuits should be able to provide bidirectional resistance not only for pushing movements but also for pulling movements in the upper limbs.

However, transmitting bidirectional resistance using a cable-driven exosuit is challenging due to the characteristic of cables, which only allow the utilization of tension for force transmission. When the actuators are mounted on the back of the body, the pushing motion of the upper limb can create resistance through cable tension because the endpoint of the cable is moving away from the actuator. Conversely, as pulling motion makes the cable moves closer to the actuator, cable routing should allow the cable to extend in the direction of lengthening to exert resistance through tension. Furthermore, exosuits are composed of soft materials to transmit force, it is necessary to design routing anchors by appropriately combining rigid structures and soft materials to efficiently transmit torque at each joint in various postures.

In this letter, we developed a cable-driven exosuit for upper limb home fitness capable of transmitting bidirectional resistance. To achieve this, a cable-driven mechanism capable of generating bidirectional resistance was developed by selecting representative exercise motions for training each upper limb muscle. To provide various intensity of resistance for target fitness motions, we applied two routing points for the pushing motion and five routing points for the pulling motion for cable routing. After validation of cable routing, we also designed and applied routing anchors for pushing and pulling exercises, considering fitness characteristics. This exosuit was controlled through a derail-preventing actuator capable of generating resistance based on the cable driven mechanism to adjust fitness intensity. We analyzed surface electromyography (sEMG) signal for verifying muscle activation with different resistance scale and compared them with resistive band commonly used in home fitness.

Fig. 1. Overall design of the cable-driven exosuit for bidirectional upper limb resistance exercises.

II. Design Methods

A. Target Muscles and Exercises

Providing bidirectional resistance based on specific muscles involved in particular movements is advantageous because it offers resistance across various motions. In the upper limb, major muscles mainly contribute to the movements of the shoulder and elbow joints, and the roles of muscles are classified based on movement [13], [14]. Based on the most representative multi-articular motions involving the shoulder and elbow, movements are divided into pushing and pulling When performing pushing and pulling motions, different muscles are primarily used. Therefore, the muscle groups can be separated into those used for pushing motions and those used for pulling motions [15], [16].

In the group of muscles that perform pushing, we selected the triceps brachii (TB), pectoralis major (PM), and anterior deltoid (AD), which are mainly involved in elbow extension and shoulder flexion (each muscle is highlighted in Fig. 2(a)–(c)). Next, in the group of muscles that perform pulling, we selected the biceps brachii (BB), latissimus dorsi (LD), and posterior deltoid (PD), which are mainly involved in elbow flexion and shoulder extension (each muscle is highlighted in Fig. 2(d)–(f)).

After selecting the target muscles, we chose specific exercises to train each one. For the muscle group involved in pushing movements, we selected kickback to train TB, chest press to train PM, and front raise to train AD (Fig. 2(a)–(c)). Similarly, for the muscles involved in pulling movements, we chose biceps curl, seated row, and face pull to train BB, LD, and PD, respectively (Fig. 2(d)–(f)).

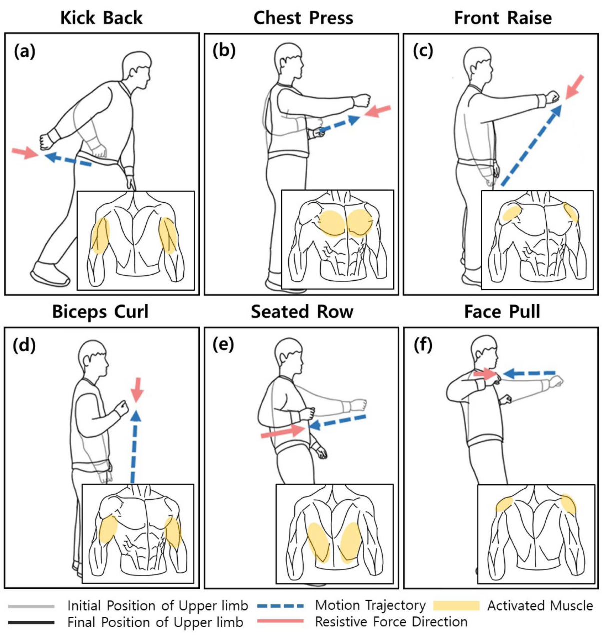

Fig. 2. Selected Exercise Motion and Target muscles. (a) Kick back for triceps brachii, (b) Chest press for pectoralis major, (c) Front raise for anterior deltoid, (d) Biceps curl for biceps brachii, (e) Cable row for latissimus dorsi, (f) Face pull for posterior deltoid.

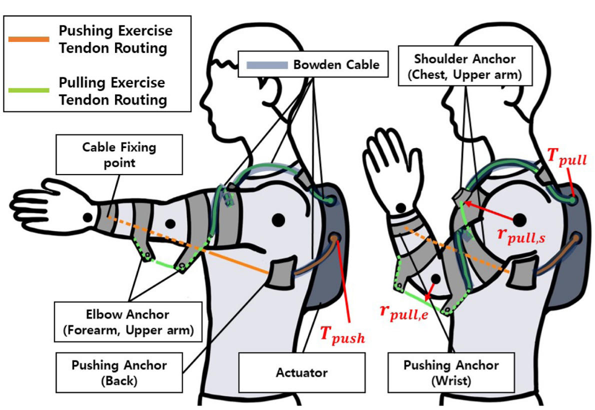

Fig. 3. Detailed explanation of the cable routing. For the pushing resistance (orange line), cable is simply connected with a back and wrist anchor. For the pulling resistance (green line), cable is connected through routing points for each joint.

B. Cable Routing

Based on the two muscle groups, separate cable routing paths have been established to resist pulling and pushing movements, enabling the transmission of bidirectional resistance. To design cable routing for bidirectional resistance, two considerations must be taken into account.

First, the cable should be routed to provide joint torque opposite to joint motion. Second, the length of the cable should increase corresponding to the joint motion while the cable is under the tension. The overall cable routing is described in Fig. 3. In the pulling exercises, the shoulder joint should undergo extension while the elbow joint should undergo flexion. Therefore, cable routing should allow for the application of opposing torques to resist these movements. For this purpose, routing points should be established on the chest and upper arm to resist extension at the shoulder joint, and on the upper arm and forearm to resist flexion at the elbow joint. Similarly, when resisting pushing exercise, the shoulder joint should undergo flexion and the elbow joint should undergo extension. In this case, two routing points can be chosen for each joint to transmit resistance. However, unlike pulling motions, when cables connected to the forearm are subjected to pushing motions, the direction of movement is lengthened. This allows for cable routing paths to be formed that transmit the desired resistance without the need to select separate routing points for each joint.

To ensure that cable routing is functioning correctly, analysis of joint torque direction and cable length variation are required. First, modeling about the designed cable routing was conducted to ensure that the torque direction for resisting pulling and pushing motions is well-formed. In the Fig. 3, $r_{pull,s}$ and $r_{pull,e}$ represent the moment arms from the cable intended for providing resistance during pushing exercises and T_{push} and T_{pull} denote the tension of each cable. Also, assuming that clockwise direction is considered positive with reference to Fig. 3.

For pushing exercises, J_s, J_e denote the Jacobian, each of exerted torque on the shoulder and elbow is as follows:

$$\tau_{push} = \left[\tau_{push,s}\tau_{push,e}\right] = \left[J_s \quad J_e\right]^T T_{push} \tag{1}$$

$$\tau_{push,s} = J_s T_{push} \tag{2}$$

$$\tau_{push,e} = J_e T_{push}. \tag{3}$$

For pulling exercises, each of exerted torque on the shoulder and elbow the tension applied to each elbow and shoulder is expressed according to the capstan equation, with each $f_e(\mu, \theta)$, $f_s(\mu, \theta)$ representing friction due to capstan effect.

$$\tau_{pull,s} = r_{pull,s} T_{pull} f_e(\mu, \theta) \tag{4}$$

$$\tau_{pull,e} = -\left|r_{pull,e}\right| T_{pull} f_s(\mu, \theta) \tag{5}$$

Therefore, total joint torque of each joint is expressed as below:

$$\tau_s = J_s T_{push} + r_{pull,s} T_{pull} f_e(\mu, \theta) \tag{6}$$

$$\tau_e = J_e T_{push} - \left|r_{pull,e}\right| T_{pull} f_s(\mu, \theta) \tag{7}$$

Based on this modeling, it is possible to apply the bidirectional joint torques by adjusting T_{push} and T_{pull}. However, in the case of the pulling resistance, the impact of friction $f_s(\mu, \theta)$ can be significant. Therefore, this should be taken into account when configuring the routing anchor.

After that, to provide resistance during the exercise, it is essential to demonstrate the changes in cable length as the user's movement progresses. To monitor these changes, a motion capture system (Optitrack Trio, NaturalPoint Inc., USA) was utilized for analyzing cable length variation in each exercise. Reflective markers were attached to the pre-established anchoring points to measure the cable length variation. One participant was asked to perform each exercise ten times. For pushing exercises, the cable variation was determined by the distance between the pushing anchors, while for pulling exercises, it was calculated as the sum of the distances between the markers attached to the routing points of the elbow and shoulder anchors. The results of

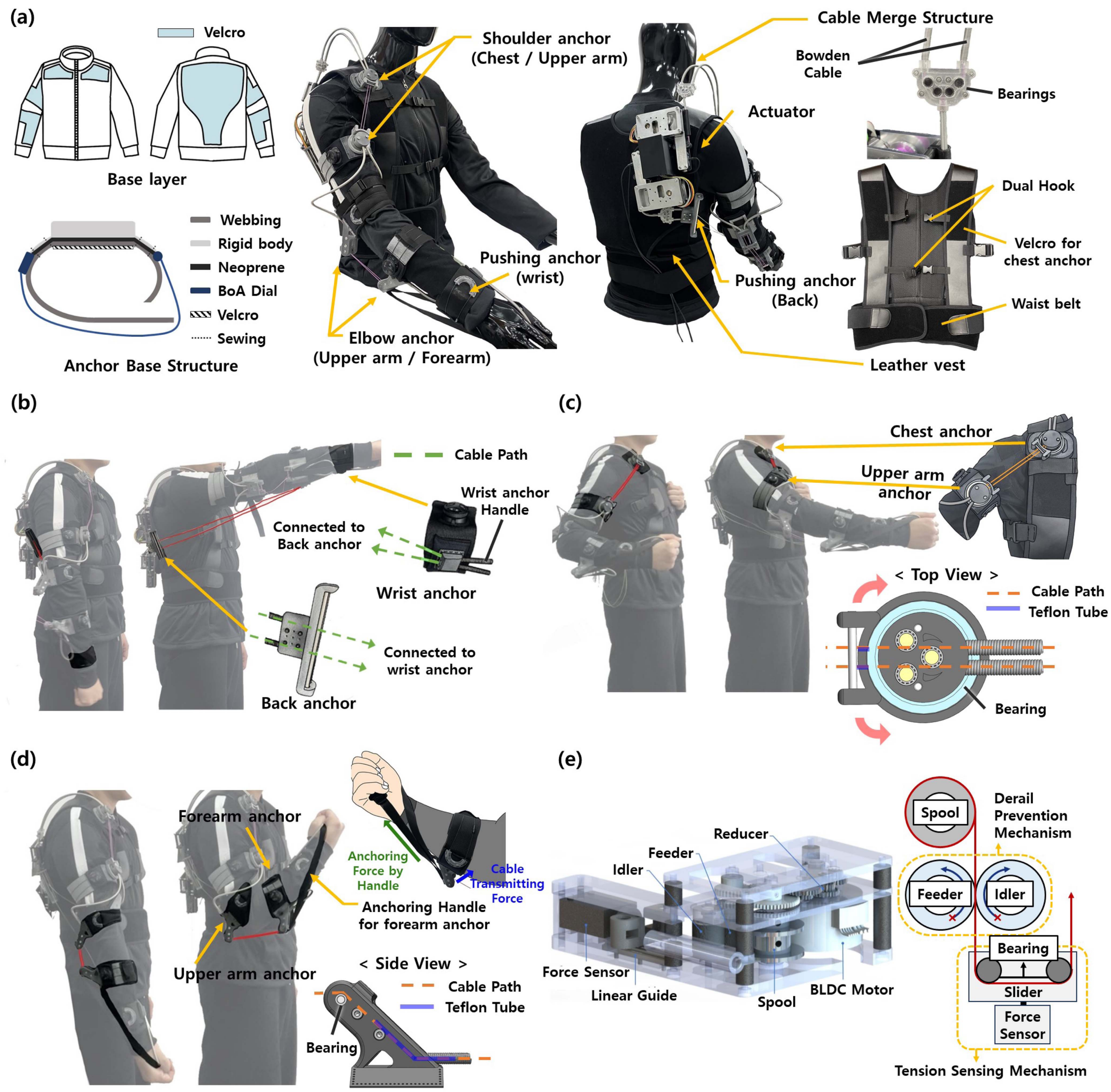

Fig. 4. Detailed explanation of the exosuit design. (a) Overall feature with base layer, anchor base structure and leather vest and cable merge structure. (b) Routing anchor design for pushing resistance with cable path (green dashed line). (c) Routing anchor design for shoulder pulling resistance with cable path (orange dashed line). (d) Routing anchor design for elbow pulling resistance with cable path (orange dashed line). (e) Overall figure of the derail-preventing actuator.

TABLE I
VARIATION IN CABLE LENGTH ACCORDING TO EACH OF EXERCISES

Pushing Exercise		Pulling Exercise	
Exercise Motion	Max. (std) [mm]	Exercise Motion	Max. (std) [mm]
Kickback	304.33 (16.2)	Biceps Curl	53.14 (0.9)
Chest press	169.55 (56.2)	Seated Row	96.9 (5.2)
Front raise	355.12 (32.7)	Face Pull	145.25 (4.9)

the variation of cable length for each exercise are presented in Table I. As the results indicate, the cable length increased with the user's movements, a trend observed consistently across all six exercise motions.

C. Exosuit Design

The proposed preliminary design of the bidirectional resistance exosuit is shown in Fig. 4. In this version, the exosuit was applied only to the right arm to verify the adjustment of bidirectional resistance and the feasibility of various exercises. The total weight of the wearable parts is 1480 g, and the weight of the actuation unit is 1250 g. The basic structure of the exosuit is shown in Fig. 4(a). This structure utilizes the sports jersey as the base layer, with a leather vest positioned on top to fix the routing anchors. Each routing anchor is fixed with Velcro and a BoA dial, allowing adjustments to fit the user's arm size. The routing anchors are constructed with neoprene to absorb shocks and are designed to wrap around the body using webbing straps. The force transmission elements, which include the routing anchors and actuators, are connected by two cables to prevent tilting from the center of the joint axis.

For the routing anchors designed for pushing exercises, they consist of back and wrist anchors. The back anchor features a bearing structure to reduce friction during movements like the

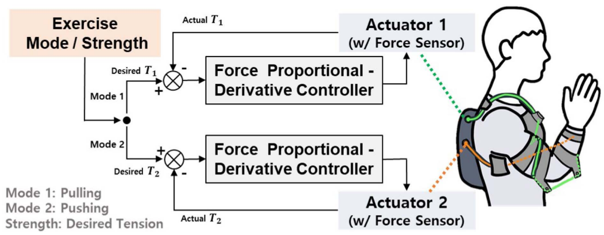

Fig. 5. Overall control architecture for this exosuit.

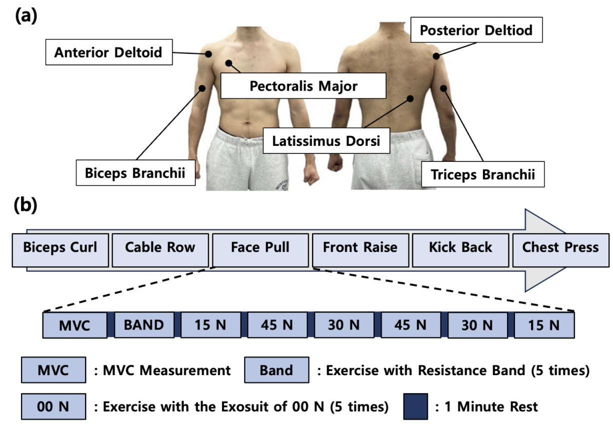

Fig. 6. (a) sEMG location for the experiment of the six target muscles, (b) Typical example of the experimental sequence.

kickback where the arms move towards the back (Fig. 4(b)). The routing anchors for pulling exercises consist of pairs of anchors, with each pair including separate shoulder and elbow anchors. The shoulder anchors are positioned on the chest and upper arm, respectively (Fig. 4(c)). A bearing structure is applied to allow circular body parts to rotate, minimizing friction during shoulder flexion/extension and abduction/adduction movements. The elbow anchors are located on the upper arm and forearm, respectively, and feature bearing structures to reduce friction during elbow flexion/extension movements (Fig. 4(d)). Additionally, they are designed in an obtuse triangular structure to increase the moment arm during elbow flexion resistance and to prevent cable interference at the elbow joint. Furthermore, to enhance anchoring performance, a handle connected to the hand was attached to the forearm anchor.

We developed a derail-preventing actuator, as shown in Fig. 4(e), which utilizes a cable-driven mechanism with BLDC motor and motor driver (Series 4221BXTH, MC 5004 P, FAULHABER, Germany) to generate more than 100N resistance, similar to the previous research [12]. It is crucial to avoid pre-tensioning of exosuit that can lead to discomfort, injuries, or diminished user efficiency. To eliminate pre-tension while maintaining actuator performance, we implemented a derail prevention mechanism consisting of a one-way bearing combined with a feeder and an idler [17], [18]. For the resistance control, MCU (Teensy 4.1, PJRC, USA) receives the data of the Exercise Mode and level of resistance intensity and utilizes the proportional-derivative control with cable tension feedback from the force sensors. The force sensor (333FDX, KTOYO, Korea) is located after the derail prevention mechanism to prevent it from being affected by the cable tension between the spool and itself (Fig. 5).

III. Verification

For the evaluation of the exosuit, three participants (age 26.7 $\pm$ 0.6 years, height 170.3 $\pm$ 0.6 cm, weight 73 $\pm$ 8.2 kg, arm reach 173.3 $\pm$ 6.51 cm) participated in the experiment. Due to the exosuit being available in a single size only, participants were selected based on similar height to ensure a proper fit of the exosuit.

A. Experimental Protocol and sEMG Signal Processing

The objectives of the experiment were to verify the effects of increasing exosuit resistance and to compare sEMG patterns between using the exosuit and a resistive band. Before beginning the exercises, maximal voluntary contraction (MVC) was measured using an sEMG sensor (Tringo Avanti, Delsys, USA), with attachment locations detailed in Fig. 6(a) [19], [20]. MVC measurements were conducted according to manual resistance guidelines with the exosuit [21]. Participants were instructed to gradually increase force against the resistance until reaching maximum effort, which they then maintained for 3 seconds before undergoing rapid muscle relaxation. Each muscle's MVC was measured three times.

After measuring MVC, participants performed exercises targeting specific muscles. Initially, they completed an exercise with a resistive band stiffness of 0.6 N/mm five times while wearing the exosuit, following proper posture guidance. Subsequently, participants engaged in six sessions, each including five repetitions of exercises at different force levels (15 N, 30 N, and 45 N), with each force level performed twice. The order of exercises and resistance levels was randomized to minimize learning effects and systemic fatigue. Throughout all sessions, participants were instructed to exercise at a comfortable speed and maintain this pace within each trial. A one-minute break was provided between sessions to mitigate muscle fatigue. Fig. 6(b) illustrates a typical example of the randomized experimental sequence.

During the experiment, sEMG signals for MVC and muscle activity during exercises were sampled at 2196 Hz. The signals were initially filtered using a band-pass filter with cutoff frequency of 20 Hz and 500 Hz. Then, the filtered signals were processed using a root mean square method with a window size of 0.1 s. Afterward, we calculated MVC and sEMG values for the exercises based on the rectified signals. The mean amplitude of the highest signal portion was used to ensure a stable results for both MVC and sEMG values, with duration of 0.52 s and 0.15 s, respectively [22], [23].

B. Effect of Adjusting Resistance Intensity

To assess whether varying the resistance levels of the exosuit significantly impact exercise intensity, a statistical significance test on the sEMG data for each resistance level is necessary. The

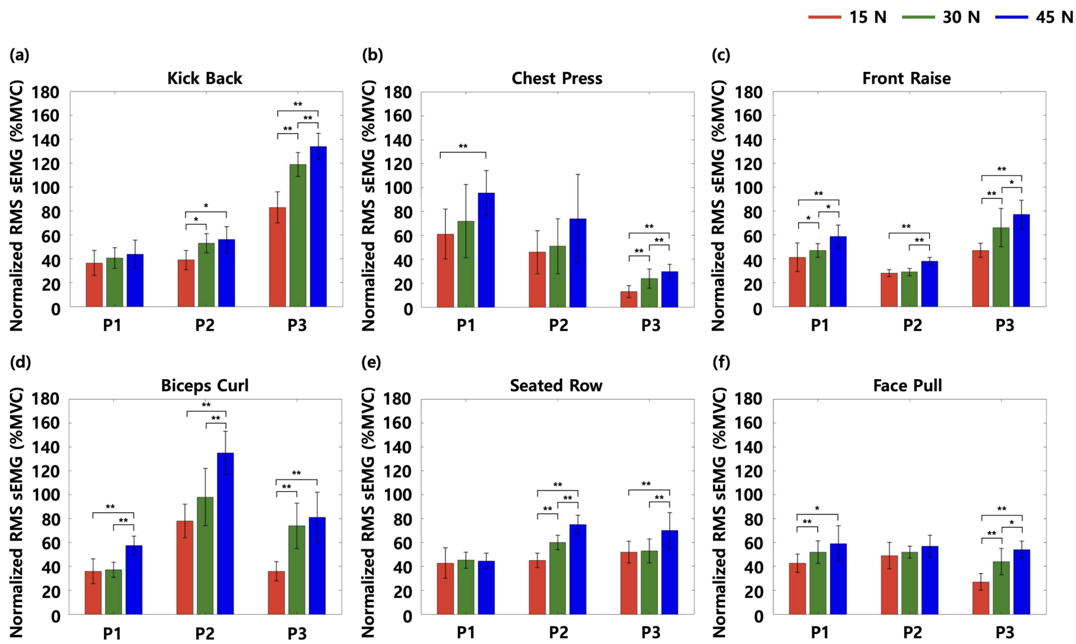

Fig. 7. Human experimental results: The levels of muscle activation for six exercises are described in (a)-(f). (a) Kick back for triceps brachii, (b) Chest press for pectoralis major, (c) Front raise for anterior deltoid, (d) Biceps curl for biceps brachii, (e) Seated row for latissimus dorsi, (f) Face pull for posterior deltoid. The symbol * and ** denote statistically significant difference with $p < 0.05$ and $p < 0.01$ respectively. Height of the bar is the mean value of sEMG data and error bar means the standard deviation of sEMG data.

Shapiro-Wilk test was first applied to evaluate the normality of the sEMG data for each exercise condition, using a significance level of 0.05. Based on the normality results, the following statistical tests were used to compare sEMG data across different resistance levels: if both groups were normally distributed, a Paired Samples t-test was employed; if only one group was normally distributed, a Mann-Whitney U test was applied; and if neither group was normally distributed, the Wilcoxon signed-rank test was used. The comparison of sEMG data was performed within each participant, as the primary objective of the analysis was to assess the effect of increasing resistance force.

Progressive increases in the resistance applied by the exosuit generally led to higher %MVC, indicating intensified exercise. Fig. 7 shows the %MVC of each exercise performed by three participants. In Fig. 7, the height of each bar represents the mean value of the data, while the error bars denote the standard deviation. When comparing the %MVC at 15 N and 45 N, a noticeable increase was observed in 14 out of 18 instances across the three participants. However, an increase in resistance of 15 N in two cases (from 15 N to 30 N and from 30 N to 45 N) resulted in a noticeable increases in only 9 and 10 instances, respectively, out of 18. The limited sample size may reduce the statistical power to definitively confirm that the exosuit can modulate exercise intensity. Nevertheless, the results suggest that adjusting resistance level gaps or increasing overall resistance can effectively alter exercise intensity, indicating that the exosuit could be a viable device for regulating exercise intensity.

Maintaining proper posture during exercise with the exosuit is crucial for ensuring target muscle engagement and maximizing exercise effectiveness. As the difficulty of the exercise posture increases, even slight deviations can result in the involvement of different muscles, making it challenging to achieve the desired exercise effects. Experimental observations suggest that varying levels of proficiency in maintaining proper posture have led to diverse impacts on the results.

The representative exercise for TB, kickback, naturally involves the engagement of the PD due to the movement's nature. When performing exercises with the exosuit, unfamiliarity with the correct kickback posture makes it challenging to maintain the instructed posture as the exercise progresses. Deviations from proper posture often result in increased involvement of the PD to complete the exercise. Consequently, there were observed instances where, despite an increase in exercise intensity, there was no significant increase in the %MVC of the TB (P1).

When performing chest press with the exosuit, the basic movement involves extending the hands forward from the sides of the chest. The activation of the pectoralis major varies depending on the direction of hand extension [24]. To measure the activation level of the pectoralis major, an sEMG sensor was attached to the sternal part of the muscle during the experiment. Consequently, even at the same resistance level, extending the hands in a direction that activates the sternal part of the pectoralis major less could result in a relatively lower %MVC. This variation in %MVC can significantly contribute to the standard deviation, which is partially observed in the experimental results of P1 and P2.

Two exercises, the seated row and face pull, involve a similar pulling motion but differ significantly in arm height during the exercise. When comparing these exercises, the %MVC of the LD and PD were similar for both, while the other four exercises demonstrated that the target muscle exhibited the highest %MVC. This observation aligns with findings from other research [25], which suggests that the similarity in exercise

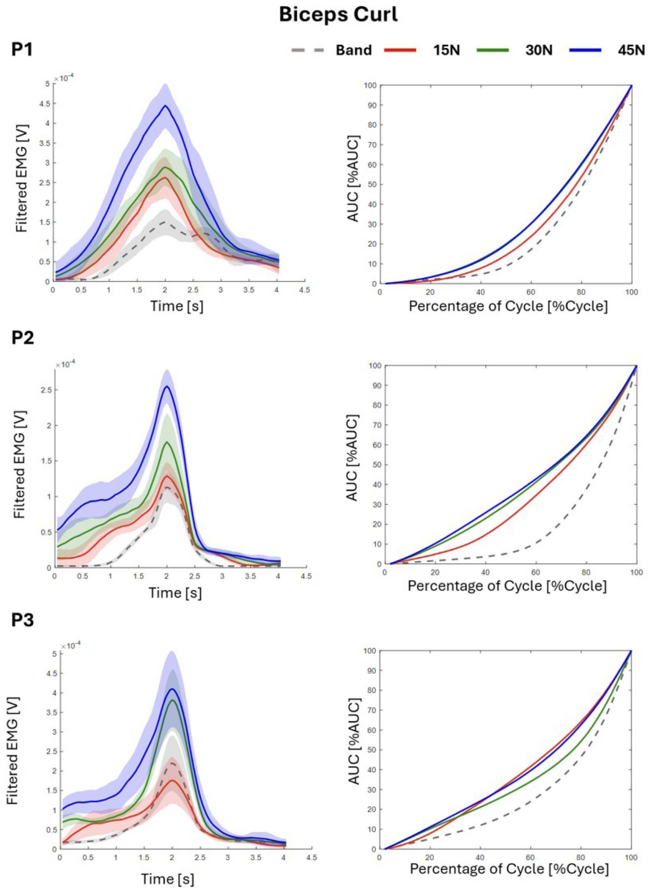

Fig. 8. sEMG profile and AUC curve of Biceps Curl. sEMG profile was aligned with the peak timings and AUC curve is calculated to compare the patterns of reaching the peak point. Highlighted lines mean average profile of 10 repetition of each exercise and shaded regions mean standard deviation of the profile.

motion may make it difficult for participants to focus on the target muscle, resulting in no significant %MVC difference between the seated row (P1) and face pull (P2). In P1, there was a slight tendency for the %MVC of the PD during the seated row to increase with strength levels, as evidenced by the following values: 15 N: 42.1 % ± 14.6 %, 30 N: 48.4 % ± 17.4 %, 45 N: 51.2 % ± 17.7 %.

Unlike other five exercises, biceps curl involves minimal interference from other muscles and requires less effort to maintain proper posture. Consequently, the effect of increasing exosuit resistance is more concentrated on the target muscle, resulting in a significant increase in %MVC between 15 N and 45 N (P1: 1.60 times, P2: 1.73 times, P3: 2.25 times greater at 45 N). These results highlight the importance of maintaining proper posture during exercises and underscore the need for sensors that measure posture and interfaces that provide posture guidance to users.

C. Muscle Activation Pattern

We compared the sEMG profile graph during the exercise between the resistive band and exosuit to identify the advantageous point of the proposed exosuit. To observe the muscle activation pattern of exercises with both exosuit and resistive band, we normalized each graph by MVC value and aligned them with the peak timings. Additionally, by utilizing the Area Under the Curve (AUC) values from the profile graph, we established a single cycle criterion as the point at which the peak is reached. We examined the %AUC versus %cycle, where the %AUC values were normalized to the AUC at the peak for each condition. This normalization allows us to observe only the pattern of actual variations. All of the results are shown in Fig.S1-S2 in the Supplementary file. The characteristic is well represented when observing the %MVC profile graph and %AUC curve of the biceps curl as shown in Fig. 8. The resistive band's resistance increases as it stretches, whereas the exosuit maintains consistent resistance throughout the movement. Specifically in the case of P3, it is observed that the at 15 N resistance for the exosuit, the peak value is lower compared to that of the band. However, in terms of %AUC, the resistance strength of 15 N for the suit shows a higher %AUC value to reach the peak. This consistency from the exosuit suggests that it can enhance muscle activation right from the initial movement. One advantage of using the exosuit rather than a resistive band for the resistance is that we can generate a specific force profile during the exercise, and this can directly change the muscle activation pattern, helping to achieve various exercise effects for the users.

IV. Conclusion

This letter proposed the development of a cable-driven exosuit designed for bidirectional upper limb home fitness, capable of providing resistance in both pushing and pulling directions. To ensure the appropriate resistance for exercises, it's essential to transmit torque in the correct direction to each joint and to arrange cable routing so that the cable length increases with the desired movements. To address these requirements, two cable routings were implemented for both pushing and pulling resistances, and these were verified through modeling and experiment. Additionally, routing anchors were designed to efficiently transmit torque across various body postures while minimizing friction. A derail-preventing actuator has been developed to enable resistance adjustment with a force sensor for proportional–derivative control. To validate the exosuit, muscle activation analysis using sEMG was performed on three healthy participants. As a result, it was confirmed that performing exercises with adjustable resistance using the exosuit can create significant differences in muscle activation. Additionally, compared to a resistive band, the exosuit can generate resistance from the initial stages of exercise, suggesting the potential to diversify muscle activation patterns.

However, as the exosuit is currently in a preliminary design stage, there are many aspects that need further development, necessitating additional research. Further research aims to develop an optimal fitness device by forming various resistance profiles and integrating it with sensors, thereby maximizing the user's fitness experience with the exosuit. Before proceeding with further research, it is essential to ensure the exosuit's completeness. Key aspects to evaluate include the weight and flippability of the exosuit, the durability of the cables, and overall usability. While the current version of the exosuit weighs

2730 g, which is relatively heavy, it is designed to offer a broader range of functionality than previous models. For comparison, a prior exosuit [12] weighed 1800 g but was limited to providing resistance exercise only for the pushing motion.

Additional exercises with the exosuit are demonstrated in the supplementary video, and we aim to explore the effectiveness of these other exercises through diverse experiments. We also plan to observe the exercise effects by applying various resistance profiles across different types of exercises and analyze how the exosuit influences long-term muscle growth, thereby demonstrating its effectiveness. Furthermore, we will develop an enhanced exosuit that provides more consistent and proper muscle training by improving the system's ability to measure and guide posture effectively.

Another advantage of the exosuit is its compact size and independence from gravity. By leveraging these advantages, the exosuit could become an ideal fitness solution for a variety of users. This includes long-distance transport workers [26], who often lack space for traditional exercise equipment, as well as astronauts [27] in zero-gravity environments, helping to address their unique fitness needs.

References

[1] S. M. Nyenhuis, J. Greiwe, J. S. Zeiger, A. Nanda, and A. Cooke, "Exercise and fitness in the age of social distancing during the COVID-19 pandemic," *J. Allergy Clin. Immunol., Pract.*, vol. 8, no. 7, pp. 2152–2155, 2020.

[2] W. R. Thompson, "Worldwide survey of fitness trends for 2022," ACSM's *Health Fitness J.*, vol. 26, no. 1, pp. 11–20, 2022.

[3] S. Yu, M. Lei, and Y. Zhan, "Home smart fitness system integrating fitness program and product design," in *Proc. 2021 5th Int. Conf. Electron. Inf. Technol. Comput. Eng.*, 2021, pp. 1610–1616.

[4] M. Schneider, A. Woodworth, and M. A. Mehrabadi, "The relationship between exercise habits and stress among individuals with access to internet-connected home fitness equipment: Single-group prospective analysis," *JMIR Formative Res.*, vol. 7, 2023, Art. no. e41877.

[5] A. Henriksen et al., "Using fitness trackers and smartwatches to measure physical activity in research: Analysis of consumer wrist-worn wearables," *J. Med. Internet Res.*, vol. 20, no. 3, 2018, Art. no. e110.

[6] N. A. Windasari and F.-R. Lin, "Why do people continue using fitness wearables? The effect of interactivity and gamification," *Sage Open*, vol. 11, no. 4, 2021, Art. no. 21582440211056606.

[7] Y. Mao and S. K. Agrawal, "Transition from mechanical arm to human arm with carex: A cable driven arm exoskeleton (carex) for neural rehabilitation," in *2012 IEEE Int. Conf. Robot. Automat.*, 2012, pp. 2457–2462.

[8] A. Ebrahimi, D. Gröninger, R. Singer, and U. Schneider, "Control parameter optimization of the actively powered upper body exoskeleton using subjective feedbacks," in *2017 3rd Int. Conf. Control Automat. Robot.*, 2017, pp. 432–437.

[9] S. Bai, S. Christensen, and M. R. U. Islam, "An upper-body exoskeleton with a novel shoulder mechanism for assistive applications," in *2017 IEEE Int. Conf. Adv. Intell. Mechatron.*, 2017, pp. 1041–1046.

[10] E. Bardi, M. Gandolla, F. Braghin, F. Resta, A. L. Pedrocchi, and E. Ambrosini, "Upper limb soft robotic wearable devices: A systematic review," *J. NeuroEngineering Rehabil.*, vol. 19, no. 1, pp. 1–17, 2022.

[11] J. Park et al., "Design of a soft wearable passive fitness device for upper limb resistance exercise," in *2022 IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2022, pp. 8488–8493.

[12] J. Park et al., "Design of a cable driven wearable fitness device for upper limb exercise," in *2023 IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2023, pp. 6456–6461.

[13] K. R. Holzbaur, S. L. Delp, G. E. Gold, and W. M. Murray, "Moment-generating capacity of upper limb muscles in healthy adults," *J. Biomech.*, vol. 40, no. 11, pp. 2442–2449, 2007.

[14] L.-R. Chang, P. Anand, and M. Varacallo, "Anatomy, shoulder and upper limb, glenohumeral joint," in *StatPearls [Internet]*. St. Petersburg, FL, USA: StatPearls Publishing, 2023.

[15] C. Barnett, V. Kippers, and P. Turner, "Effects of variations of the bench press exercise on the EMG activity of five shoulder muscles," *J. Strength Conditioning Res.*, vol. 9, no. 4, pp. 222–227, 1995.

[16] Á. Illyés and R. M. Kiss, "Shoulder muscle activity during pushing, pulling, elevation and overhead throw," *J. Electromyogr. Kinesiol.*, vol. 15, no. 3, pp. 282–289, 2005.

[17] H. In, U. Jeong, H. Lee, and K.-J. Cho, "A novel slack-enabling tendon drive that improves efficiency, size, and safety in soft wearable robots," *IEEE/ASME Trans. Mechatron.*, vol. 22, no. 1, pp. 59–70, Feb. 2017.

[18] S. Cheon et al., "Single EMG sensor-driven robotic glove control for reliable augmentation of power grasping," *IEEE Trans. Med. Robot. Bionics*, vol. 3, no. 1, pp. 179–189, Feb. 2021.

[19] H. J. Hermens, B. Freriks, C. Disselhorst-Klug, and G. Rau, "Development of recommendations for semg sensors and sensor placement procedures," *J. Electromyogr. Kinesiol.*, vol. 10, no. 5, pp. 361–374, 2000. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1050641100000274

[20] J. R. Cram, G. S. Kasman, and J. Holtz, "Introduction to surface electromyography," Aspen publishers, 1998.

[21] O. J. Quittmann, J. Meskemper, K. Albracht, T. Abel, T. Foitschik, and H. K. Strüder, "Normalising surface EMG of ten upper-extremity muscles in handcycling: Manual resistance vs sport-specific MVICs," *J. Electromyogr. Kinesiol.*, vol. 51, 2020, Art. no. 102402. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1050641120300171

[22] P. Konrad, "The ABC of EMG," *Practical Introduction Kinesiological Electromyogr.*, vol. 1, no. 2005, pp. 30–5, 2005.

[23] S. Rota, I. Rogowski, S. Champely, and C. Hautier, "Reliability of EMG normalisation methods for upper-limb muscles," *J. Sports Sci.*, vol. 31, no. 15, pp. 1696–1704, 2013.

[24] J. D. Lauver, T. E. Cayot, and B. W. Scheuermann, "Influence of bench angle on upper extremity muscular activation during bench press exercise," *Eur. J. Sport Sci.*, vol. 16, no. 3, pp. 309–316, 2016.

[25] R. Bergquist, "Assessment of muscle activity using elastic resistance in strength exercise," Master's thesis, NTNU, Trondheim, Norway, 2015.

[26] H. L. Naug et al., "Occupational health and metabolic risk factors: A pilot intervention for transport workers," *Int. J. Occup. Med. Environ. Health*, vol. 29, no. 4, pp. 573–584, 2016.

[27] S. Trappe et al., "Exercise in space: Human skeletal muscle after 6 months aboard the international space station," *J. Appl. Physiol.*, vol. 106, pp. 1159–1168, 2009.