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Muscle Synergy Shifts via Real-Time sEMG-Based Vibrotactile Biofeedback

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I. Introduction

Weight training aims to develop and maintain a healthy body, but despite its benefits, it's associated with injuries and musculoskeletal disorders [1], particularly among beginners who often use incorrect muscle patterns. Experienced weightlifters can selectively activate specific muscles during training, facilitating appropriate muscle recruitment, while novices typically face three key challenges:

a. Unintended muscle growth due to lack of spatial awareness: Overactivation of uninvolved muscles during training can lead to unintentional muscle growth [2], resulting in muscular imbalances and potential injuries to both target and synergist muscles.

b. Premature muscle fatigue due to suboptimal movement execution: This results from insufficient awareness of temporal coordination between muscle activation and movement changes [3], and limited knowledge of appropriate exercise intensity requirements.

c. Increased injury risk: Muscle imbalances and improper movement patterns, specifically overactivation of synergist muscles, can lead to compensation and increased strain on target muscles [4].

Previous biofeedback-based guidance systems [5] have limitations: they provide information over longer time frames than typical weight training repetitions (under 10 seconds), rely on onset detection rather than intensity measurement, and visual systems fail to match feedback to actual muscle locations. To address these gaps, we propose a haptic feedback system that transmits expert-level muscle activation data to novices in real-time through vibrotactile feedback based on surface electromyography (sEMG).

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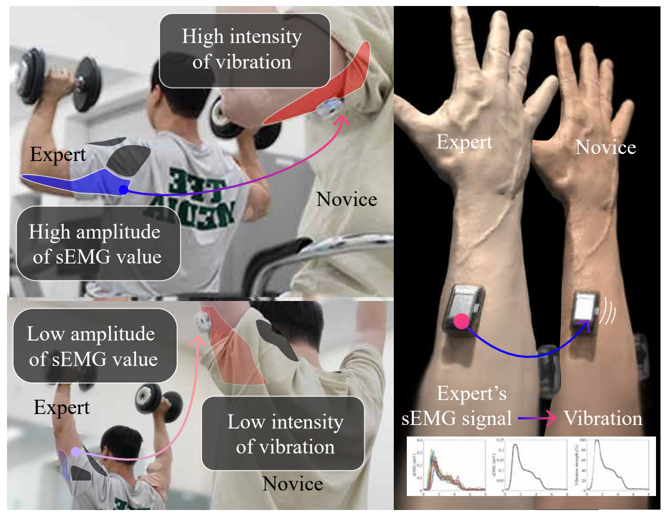

Fig. 1. The proposed sEMG-based vibrotactile biofeedback system involves wearable devices that measure surface electromyography signals and deliver vibrotactile feedback. Both the expert and the novice wear these devices, and the muscle activation level of the expert is conveyed to the novice through corresponding vibration intensity.

II. Preliminary Test

To examine differences between experts and novices in muscle recruitment and activation timing, we conducted a preliminary study with 12 healthy adult participants (6 experts with at least three years of continuous weight training experience, 6 novices without formal training). Participants performed seated tricep extension, lat pull down, and seated shoulder press with their eight-repetition maximum load (8 RM). We collected sEMG data from seven muscles: biceps brachii (BB), triceps brachii longhead (TBl), anterior deltoid (DELTa), posterior deltoid (DELTp), upper trapezius (TU), latissimus dorsi (LD), and pectoralis major (PM). The sEMG signals were processed using Butterworth band-pass filtering, rectification, normalization, and root mean square feature smoothing. Analysis revealed significant differences between expert and novice participants:

a. Spatial domain: Experts demonstrated greater activation of primary muscles and more efficient recruitment of synergistic muscles compared to novices. For example, during triceps extension, experts primarily used triceps brachii when lifting and posterior deltoid when lowering, while novices recruited upper trapezius when lifting and latissimus dorsi when lowering.

b. Temporal domain: Experts demonstrated earlier peak activation and shorter activation durations in primary muscle

TABLE I
RECRUITED PRIMARY AND SYNERGIST MUSCLE

SubjectType	Muscle	Triceps Extension		Lat Pull Down		Shoulder Press	
		Pull	**Push**	**Pull**	Push	**Push**	Pull
Expert	Primary	LD	TBl	LD	TBl	DELTa	DELTa
	Synergist	TBl	DELTa	TBl	DELTp	TU	LD
Novice	Primary	LD	TU	LD	LD	DELTa	LD
	Synergist	TU	LD	PM	DELTp	LD	TU

groups. During shoulder press, experts showed more coordinated activation of triceps brachii, posterior deltoid, and latissimus dorsi compared to novices, suggesting experts can properly recruit muscles according to the exercise by utilizing different muscle groups based on changes in weight load and movement direction.

The primary and synergist muscles, judged based on the relative muscle activation, are as shown in Table. I.

III. DEVICE DESIGN

Based on preliminary findings, we developed a wireless sEMG-based vibrotactile biofeedback system. The system operates with a leader-follower structure where follower devices transmit quantized 8-bit sEMG signals to the leader device (PC) via BLE 5 wireless communication. The transmitted signals are converted into vibration motor control commands and sent back to the follower devices. PWM duty is calculated based on rectified, windowed sEMG signal with considerations for individual resting sEMG signal and motor gain. The device processes sEMG data in real-time at approximately 800 Hz, enabling immediate feedback on muscle activation patterns and intensity. The system was evaluated for vibration performance using a 3-axis accelerometer in various attachment conditions.

IV. EXPERIMENTAL PROTOCOL

The system was evaluated through an experimental protocol involving 11 participants, including 5 experts and 6 novices. The protocol consisted of several stages. First, psychophysical tests were conducted to examine vibration perception in the TBl and DELTp muscles. Next, sEMG electrodes were attached, followed by a warm-up session. Participants then performed 8 RM trials in the experimental environment. The main experimental session was carried out using a Latin square design across six different conditions: CONT (no guidance), VIS (visual observation), VIS+VIB (constant vibration), VIS+BIO (sEMG-based vibration with visual feedback), VIS+BIO-SUD (sEMG-based vibration without sound), and BIO-SUD (vibration only). After completing the tasks, participants filled out the NASA-TLX questionnaire to assess their perceived workload. sEMG signals were recorded from 14 sensors placed on seven muscles of both the expert and novice participants, with a sampling rate of approximately 1259 Hz.

V. RESULT

The psychophysical perception experiment demonstrated that both experts and novices were more sensitive to vibration at the anterior deltoid compared to the triceps brachii, with the difference more pronounced in experts. This suggests the need for location-specific calibration in biofeedback system design. In terms of muscle coordination, the normalized muscle activation patterns across the exercise cycle showed that experts exhibited more focused and precise muscle activation patterns, particularly during the VIS+BIO-SUD condition. Linear correlation analysis quantified these differences, with the best-case scenario demonstrating improved correlation in deltoid muscle activation when using the biofeedback system, particularly in the VIS+BIO-SUD condition. Compared to the preliminary test, the vibrotactile experiment showed a more distinct difference in muscle synergy shifts, particularly in the latissimus dorsi functioning as a synergist during the pull motion of the shoulder press. NASA-TLX results indicated that when biofeedback was applied, participants perceived themselves as performing the task more successfully compared to conditions without biofeedback, with statistical significance in the performance category.

VI. DISCUSSION AND FUTURE WORK

Our study offers important insights for muscle training and biofeedback system design. The varying sensitivity to vibrotactile feedback across muscle groups highlights the need for location-specific calibration of feedback intensity. Our real-time sEMG-based vibrotactile system addresses prior limitations by delivering immediate, targeted feedback without requiring visual attention, and introduces a novel use of expert muscle activation patterns as reference signals for motor learning. Novice users receiving vibrotactile feedback showed better timing in muscle activation, especially during transitions between concentric and eccentric phases, suggesting faster skill acquisition. The system's ability to guide movement without visual or auditory cues indicates that proprioceptive feedback alone can be effective. NASA TLX results further support its ability to reduce perceived effort and cognitive load. Future improvements may include higher temporal resolution, personalized calibration for individual differences, application to lower-body exercises, and integration with machine learning for advanced pattern recognition.

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