Exploring the Utility of Curvilinear Feedback Systems for Improving Muscle Strength via Surface Electromyography

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Abstract

Our knees play a crucial role in our everyday lives and mobility; however, their constant use leads to life-changing injuries such as osteoarthritis and ligament tears. Recent advances in knee-related interventions have focused on enhancing the recovery process, with a particular emphasis on the Vastus Medialis Oblique (VMO), a quadricep muscle pivotal for knee stability. The strengthening of this muscle can be beneficial for those recovering from knee-related injuries. Utilizing surface electromyography (sEMG) to measure muscle contractions, behavior analysts can provide feedback and establish contingencies for promoting stronger VMO contractions. While previous studies have worked with discrete schedules of reinforcement, this study utilizes conjugate schedules that mirror real-world contingencies. We compare two types of curvilinear relations in the conjugate schedule, influencing the relation between muscle response and feedback. In one condition, a negatively accelerating relation was created, where low-to-moderate muscle contractions produced the greatest amount of reinforcement. The other arrangement featured a positively accelerating relation, where highly intense contractions would be most reinforced. Results showed that all eight participants had their strongest contractions under the positively accelerating relation. Six of them also demonstrated higher average amplitudes within that same condition, providing insight into the efficacy of curvilinear relations in shaping VMO contractions.

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As the body's largest joints, our knees play an important role in simple maneuvers such as bending down, sitting, walking, and running (Wu, 2014). However, constantly using them results in a high risk of injuries, such as fractures, sprains, dislocations, and ligament tears. Moreover, the cumulative stress and pressure exerted on the knee joints connecting the thigh to the leg can lead to several debilitating conditions.

The natural wear-and-tear consequence takes a toll on the knee joint, gradually eroding the cartilage that acts as a cushion between the bones. The deterioration, leading to bones rubbing against one another, results in a common knee-related issue known as osteoarthritis (OS) within the knee, affecting a significant portion of the population (Zhang & Jordan, 2010). This becomes a substantial setback for middle- and older-aged adults with cartilage and ligament degradation that will impact not only their mobility but also their overall well-being and independence (Ibeachu et al., 2019). This is not to mention the associated cost for the medical and rehab procedures.

Age is not the only factor involved in knee-related incidents. Athletes, in particular, face the rigor of sports activities, pushing their bodies to the limits. Knee injuries constitute almost half of their injuries (Truong et al., 2020). The most common of these is related to the ligament responsible for knee stability, the anterior cruciate ligament (ACL). ACL tears and sprains constitute the majority of knee injuries (Benjaminse et al., 2006). The considerable recovery period lasts between 3 to 12 months (Filbay & Grindem, 2019). Such a hindrance results in time off from work and family duties, demanding rehabilitation at a facility.

The development of effective knee-related interventions would improve the quality of life for many people of all ages and professions. Among the necessary elements involved in knee stability is a quadricep muscle called the Vastus Medialis Oblique (VMO; Abelleyra et al., 2023). This muscle plays a vital role in stabilizing our knees, enabling a person to stand up and walk. What makes the VMO important in the context of knee injuries is its ability to handle some of the load that would otherwise burden the knee joint. By focusing on strengthening the VMO, interventions can assist in mitigating knee injuries (Chang et al., 2015). Methods can be incorporated to promote frequent VMO contractions, proving especially useful for physical therapy, rehabilitation, and healthcare in general. The targeted exercises not only enhance knee stability but also contribute significantly to overall muscle strength (Chang et al., 2015).

Yet, one ongoing challenge persists: the precise quantification of muscle contractions. Most behaviors that are being studied are overt and can be monitored. Researchers can measure dimensions of overt behaviors during observations, such as count or duration of movement. Muscle shortening, on the other hand, is a covert behavior that cannot be seen. A different method of measurement other than direct observations is required. One prominent discovery was the efficacy of biofeedback, a therapeutic technique that involves monitoring instruments to provide individuals with real-time information about such physiological conditions as heart rate, skin temperature, and even muscle tension (Dana et al., 2010). Biofeedback has been implemented to evaluate athletic, academic, and business performances. Health and wellness also have improved from the monitoring capabilities of biofeedback. One technique to study muscle signals is the use of surface electromyography (sEMG) in biofeedback (Dana et al., 2010). This method detects the electrical pulses that characterize muscle contraction (Reaz et al., 2006) and serves as a benchmark for its strength, distinguishing between strong and weak muscular efforts.

Armshaw et al. (2022) summarized multiple studies that used sEMG to evaluate a host of other knee-related injuries and found studies centered on arthroscopic meniscectomy (Akkaya et al., 2012; Kinap et al., 2005; Oravitan & Avram, 2013), knee osteoarthritis (Anwer et al., 2013; Choi et al., 2015; Raeissadat et al., 2018; Yilmaz et al., 2010), patellofemoral pain syndrome (Dursun et al., 2001; Ingersoll & Knight, 1991; Ng et al., 2008; Wise et al., 1984), and recovery from ACL surgery (Christanell et al., 2012). All of the studies utilized one of two forms of feedback: an auditory tone or visual graphical display. Half of these studies showed statistically significant improvements after sEMG intervention (Akkaya et al., 2012; Anwer et al., 2013; Choi et al., 2015; Kinap et al., 2005; Ng et al., 2008; Yilmaz et al., 2010).

In a recent study, Vaidya and Armshaw (2021) utilized surface electromyography biofeedback (sEMGBF) to develop a method to obtain the maximum voluntary isometric contraction (MVIC). Accurate measurement of the MVIC allows for more accurate reinforcement criteria based on the MVIC. Using an sEMG device, the researchers measured the amplitude – in units of microvolts (μV) – of each VMO contraction. They then used sEMGBF to deliver reinforcement when muscle contractions met or exceeded a predetermined threshold, encouraging stronger VMO muscle contractions. The study applied three types of contingencies: instruction only, auditory feedback, and a game. Results across nine university students showed the highest amplitudes when participants played the game. These results suggest that the overall contribution of behavior principles may aid in muscle rehabilitation and future technological advancements. The different conditions highlight the complexities involved in reinforcing muscle contractions. The effectiveness of these methods is intricately tied to the specific contingencies in place, the type of feedback provided, and the manner in which instructions are given. Moreover, the presence or absence of gamification elements further influences the diverse range of responses observed in individuals.

Taken together, these studies suggest that contingencies of reinforcement can have an impact of muscle contractions—that is, that every participant must meet a criterion to produce reinforcement. However, the above studies all used discrete schedules in which reinforcement was all-or-nothing, neglecting the contraction values between the initial and final moment. We believe it is critical to provide moment-to-moment reinforcement for each small response as well. We want to give more opportunities for participants to observe, adjust, and correct their behavior in real time. This can be accomplished with a conjugate schedule of reinforcement as a form of feedback.

Conjugate schedules are a type of reinforcement schedule in which the intensity or rate of reinforcement varies with properties of the target behavior. Such schedules can be observed in countless aspects of everyday life. For example, when using a gaming controller, the amount of force pushed against the joystick will be proportionally reflected in the speed of a character who is moving across the screen. While driving a vehicle, the more the steering wheel rotates, the sharper a turn the car will take. In the case of lifting weights, the more force your muscles exert, the more the weights will move. The nature of the conjugate schedules in all these examples influences the way a person can play, work, and, in general, behave. An arranged conjugate schedule can more closely resemble everyday contingencies than can a discrete schedule.

Conjugate schedules have been investigated in various behavioral contexts. The first use of conjugate schedules was that of Lindsley (1957), evaluating sleep deprived patients. Participants wore earphones that continuously emitted a tone, the decibels of which were proportional to the rate of pressing a microswitch. They could completely silence the tone with a high enough rate of pressing, resulting in every participant having high rates of button pressing before falling asleep.

Lindsley (1957) would inspire new work with conjugate schedules on infants. Lipsitt et al. (1966) used a panel-pressing procedure with a dimly lit television. The panel had a button that, when pressed, would increase the screen's brightness. Given a rapid pressing rate, infants produced a proportionally brighter image. The conjugate schedule produced a significant increase in button pressing for every infant. Other research evaluated an infant-mobile preparation in which infants could influence the movement of a crib mobile via a cord connecting the infant's ankle to the mobile (Rovee, & Rovee, 1969; Rovee-Collier & Capatides, 1979). Those experiments showed that conjugate schedules can produce rapid acquisition and consistently high rates of infant interaction with a crib mobile. Siqueland and DeLucia (1969) developed another conjugate schedule procedure known as the high-amplitude-sucking (HAS) procedure. An infant would exert force on a suction-measuring device. The stronger the suction force applied on it, the clearer a projected visual image would become. All participants gave sustained responses with high amplitudes.

Williams and Johnston (1992) and Rapp and Vollmer (2005) argued that conjugate schedules are involved in many typical activities such as walking, running, and even ice skating. Williams and Johnston (1992) compared conjugate to discrete schedules of reinforcement, having participants turn the wheel of a projector that displays reading material. Participants were instructed to read as many words as they could, and the assigned reinforcement was either discrete or conjugate. The largest percentage of words read came from the conjugate schedule. Rapp (2008) found that conjugate schedules can maintain automatically reinforced behavior, such as hand flapping, even in the presence of punishment. A later work utilized auditory stimulation as a conjugate schedule of reinforcement (Falligant et al., 2020). Our study will investigate the effect of a particular variation of the conjugate schedule that alters how behavior will be reinforced.

Our variation can be best characterized as a curvilinear relation between behavior and reinforcement. Also recognized as a contingent reward magnitude, this procedure falls in the domain of what Lipmann (1973) describes as the relation between one's performance and the magnitude of reinforcement. This type of contingency presented a similar representation of real-world contingencies (Lipmann, 1977). Lipmann (2000) experimented on a nonlinear association between a response's frequency and its reward magnitude. For the study, participants must count the number of "A" and "B" that appeared on a screen with the goal of earning 15 maximum points. The differences were a negatively or positively related reward contingency for a session. More specifically, the negatively related reward contingency reduced the score by 5 for each response, whereas the positive relation added 5 points. A modification in one of the experiments had a gradual change in points, starting at 1 point before raising up or down with increased number of responses. The results indicated a very low frequency of responses with the negatively related reward contingency. The opposite effect occurred with the positive counterpart, with participants responding at moderate to high rates. These results show that a nonlinear relation between behavior and reinforcement can influence a person to do more or less.

Combining both sEMG and conjugate schedules of reinforcement, the purpose of this study is to examine the effect of different curvilinear relations between the amplitude of VMO contractions and reinforcing feedback. Participants were exposed to two types of conjugate schedule. In one, there was a negatively accelerating relation between response intensity and feedback. This will correspond to low to mid-intensity contraction responses producing the largest increases in the amount of reward presented. In the second condition, there was a positively accelerating relation between response intensity and feedback. We will observe how the different types of curvilinear relations influence the amplitude of the VMO contractions.

Method

Participants and Setting

A total of eight university students participated in the study with their ages ranging from 18 to 24. All participants were in good health at the time of the experiment. None of the participants showed any form of auditory impairment. In all experiments, the participants sat in chair in a small room. The timeframe of each session varied across participants based on their availability, but a majority of the sessions ran from noon to evening. A single session required approximately 20 to 30 minutes to complete.

Flexdot

A Flexdot is a custom sEMG Bluetooth device that allows for the measurement of the electroactivity within the VMO muscle. The device is a small 2 in by 2 in white, rectangular sensor that attaches to the surface of the skin via adhesive electrodes – circular, adhesive pads. There are three ports on the FlexDot where three electrodes connect to the device. It can then detect and read the electroactivity of the muscle beneath the skin. A small 3V lithium coin battery powers the device.

The device connects via Bluetooth to a custom-developed Android app on a tablet or cellular device. This app allows for the measurement of contractions and the arrangement of contingencies. It can also deliver the two types of reinforcers in the study: auditory and conjugate visual feedback. The auditory feedback comes in the form of a high-pitch bell sound to signal that the participant has met the contraction criterion. The conjugate visual feedback is implemented as a progress bar that, based on the intensity of the muscle contraction, can continuously fill up. More details are described below.

Experimental Design

The dependent variable of interest is the intensity of muscle contraction, measured in µV, the unit in which muscle electrical impulses are measured. The higher the voltage, the more contracted the muscles. The lower the voltage, the more relaxed the muscles. Still, even a muscle will still produce around 20-40 µV while at rest. The type of curvilinear relation condition is the independent variable. Each experimental session consisted of three phases, as shown in Table 1. Each phase is described in detail below.

Table 1

An Outline of the Experimental Design

Phase	Group Type	
	A	B
1^{st}	R-MVIC	R-MVIC
2^{nd}	Decay	Growth
3^{rd}	Growth	Decay

Note. All participants completed the R-MVIC test. The Growth and Decay conditions were counterbalanced.

General Arrangements

Each trial was initiated with the application instructing the participant to “Flex.” Trials lasted 3 seconds, during which participants engaged their VMO muscle. A trial ended when the application instructed the participant to “Relax.” Trials were separated by a 5-second intertrial interval, during which participants could rest their muscles. EMG measurements were averages obtained at quarter-second intervals in real-time, resulting in four data points per second. There are 10 to 12 trials in each experimental phase of the study. The auditory-feedback criterion was set in accordance with the phases discussed below. A progress bar in the app provided visual feedback to the participant. The conjugate schedule was implemented with this progress bar. The max value of the bar depended upon the R-MVIC value obtained, described below.

R-MVIC

A reinforcement-based maximum voluntary isometric contraction (R-MVIC) procedure estimates the maximum capability of contracting one’s muscles. This estimate is obtained when the participant completes three consecutive sets of four trials – or contractions. The steps were as follows: the experimenter requested the participant’s readiness. The first trial had a criterion of 1000 µV. The second trial was changed to 2000 µV. The third trial would be 3000 µV with the fourth raised to 50,000 µV. This essentially creates an extinction trial, given that it is an unattainable criterion. Such a trial was expected to produce an “extinction burst,” evoking a high amplitude of contraction from the participant, given the contingency created from the three trials prior (Fisher et al., 2022). The entire process totaled 12 contractions. The individual then is allowed to rest for 3 minutes. At the completion of three trials, an average was taken from all three extinction trials, and that value was increased by 125%. This value was considered to be their R-MVIC or baseline value.

Negatively Accelerating: Decay

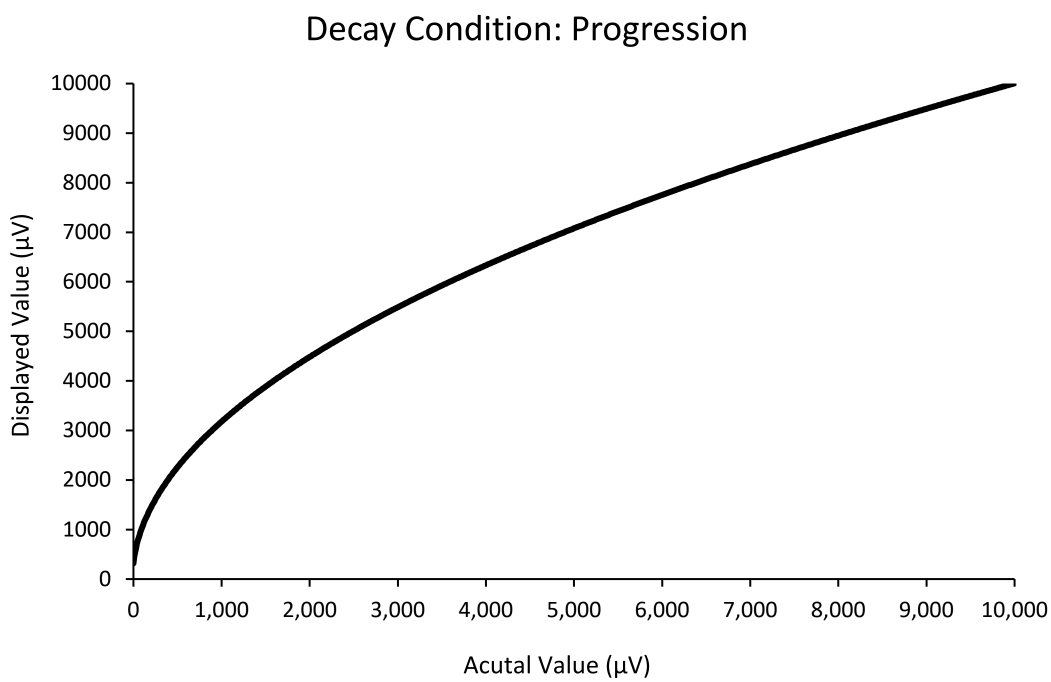
This phase began with the selection of the Decay category within the app. The participant was given a tablet that displays the app and its progress bar. Their objective was to fill the progress bar for each trial. This condition consisted of 10 trials before the tablet was returned to the experimenter. Given the counterbalancing of phases, if this was the last phase, the experiment concluded. Otherwise, a 3-minute break was provided to the participant before completing the Growth phase.

Equation (1) shows the function determining how the progress bar filled. It is a power function with a negative acceleration between the obtained EMG values and those displayed. The z parameter represents the steepness and difficulty of the schedule while the b parameter corresponds to the R-MVIC value. For all participants in the current study, z was set to 0.5, in order to balance the difficulty of the schedule. Each measured value, corresponding to the x variable, is inputted into equation (1) to determine the displayed feedback value. This value is reflected on the progress bar in real time.

$$y_1 = \frac{b}{b^z} \cdot x^z \tag{1}$$

Figure 1

Decay Relation of Response and Conjugate Reinforcement



Note. This figure indicates the amount at which the progression bar fills up in relation to the number of microvolts produced by the participant's VMO. The R-MVIC value, or b parameter, has been arbitrarily set to 10,000 µV.

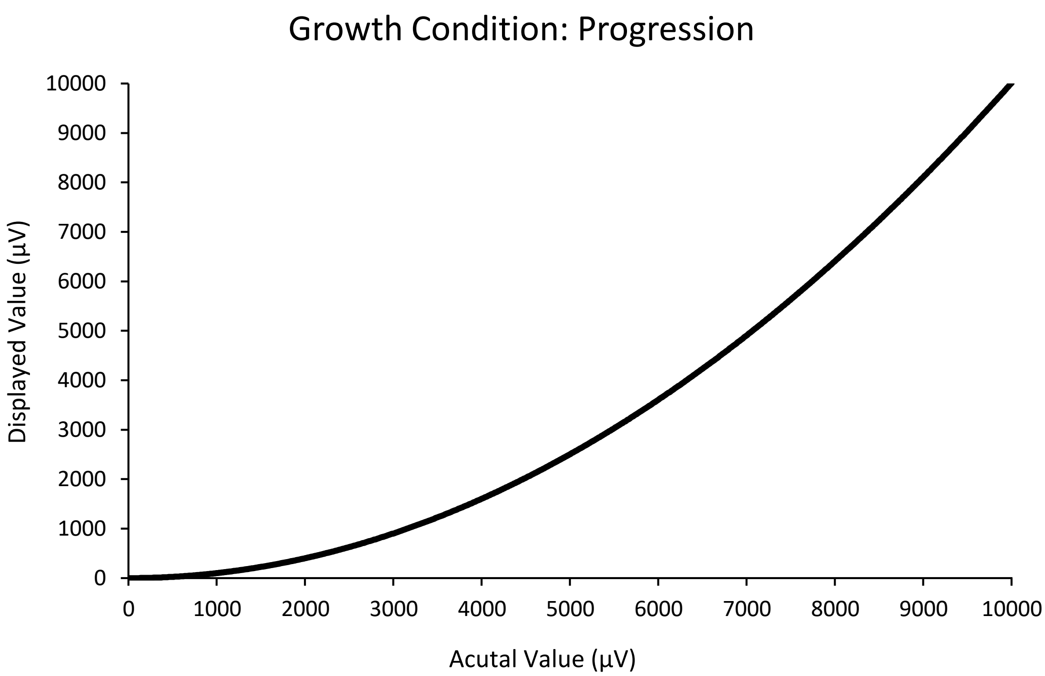
Positively Accelerating: Growth

This phase required the selection of the Growth category. The remaining procedures were identical to the Decay phase. Equation (2) shows the function determining a positively accelerating conjugate schedule of reinforcement. The meaning of each parameter is identical to equation (1) in the Decay condition.

$$y_2 = \frac{b}{b^{\frac{1}{z}}} \cdot x^{\frac{1}{z}} \tag{2}$$

Figure 2

Growth Relation of Response and Conjugate Reinforcement



Note. This figure indicates the amount at which the progression bar fills up in relation to the number of microvolts produced by the participant's VMO. The R-MVIC value, or b parameter, has been arbitrarily set to 10,000 µV.

Procedures

The participant is seated in a chair as the researcher read the following script:

Thank you so much for attending our session today. Before we begin, I ask for your consent to use the data we will gather today to further better understand how we can improve the efficiency and efficacy of rehabilitation. What you are going to do is contract your muscles, specifically a knee muscle called the Vastus Medialis Oblique muscle

(VMO). It is located right here. And to help me, I will be placing this gadget on your VMO. This is a Flexdot and it will measure how hard you are flexing. It has three pads (called electrodes), and they have some adhesive to be able to stay in place throughout our trial. No shocks are involved; if anything, this will merely measure the electricity that you produce naturally. We will also have an app and this app will have audio and visual cues to instruct you through the process. There are two prompts: flex and relax. And you'll contract or relax when you hear those phrases. Just make sure to be seated down, back straighten, and your feet being flat on the floor at all times. We are going through four phases (about 10 flexions in each), the first will be different from the rest. You will only hear a ding, and that sound means you have flexed the minimum amount. Flex as hard as you can until you hear that ding. The other three tries, we will have you hold onto my device that'll display a bar and your goal is to contract and fill that bar and keep it filled during the time you have to contract. Do you have any remaining questions or concerns before we start?

After all questions and concerns were answered, the sEMG device was placed on the surface of the subject's skin above the VMO. Before each experimental condition, the researcher reminded the subject to keep their feet flat on the ground and back straightened against the chair. Every participant initially proceeded through the R-MVIC condition.

Depending on the group assignment, the participant either advanced to the Decay or Growth phase. After that phase was completed, the participant ran through the other phase that they did not do at first. The session was complete after the participant completed all three phases.

Results

Table 2 shows the baseline values for each participant in the study, reflecting individual variations in strength. These baseline, or R-MVIC, values will serve as reference points throughout the subsequent analyses and figures.

Table 2

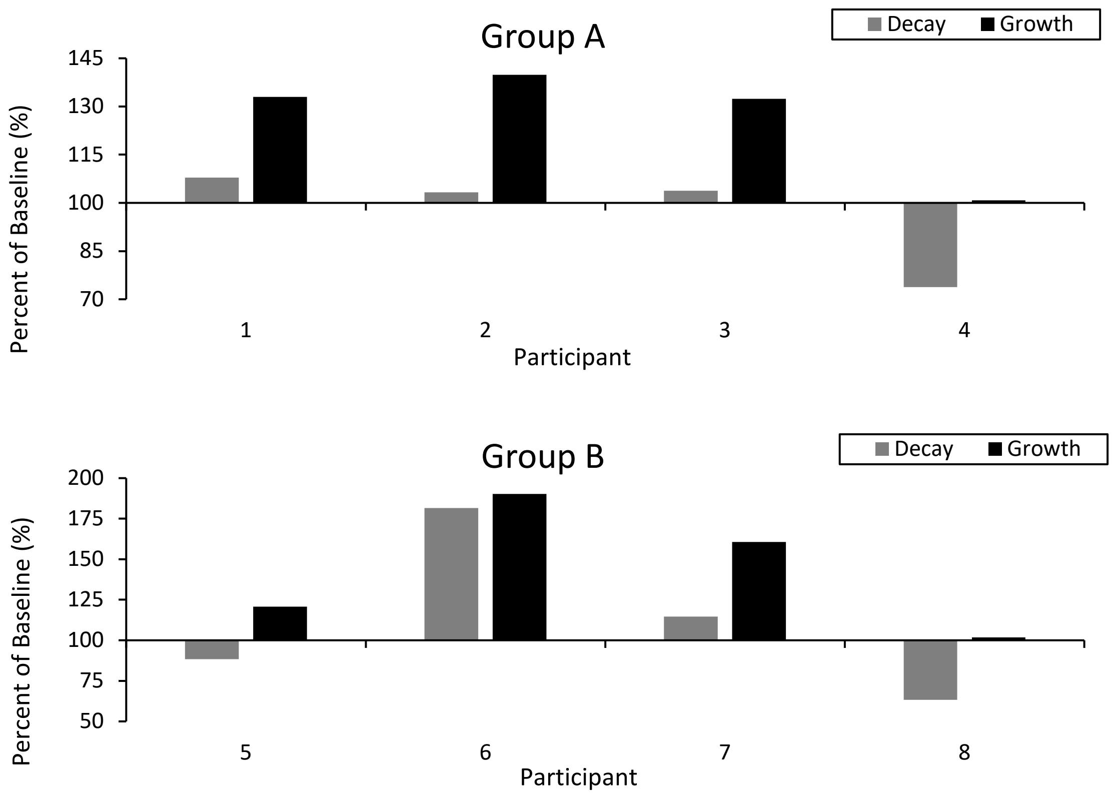
Baseline (R-MVIC) Values of Each Participant

Participant	1	2	3	4	5	6	7	8
Baseline (μV)	8125	10461	3907	12860	11305	5282	9298	16617

Figure 3 shows the maximum contraction amplitude as a percent of baseline value for each participant. Three of the eight participants have lower peak values than their baseline for the Decay condition. Every participant in the Growth condition exceeded their baseline value, ranging from 101% to 181% of their baseline. The Growth condition also produced greater peak amplitudes than the Decay condition across all participants.

Figure 3

Percentage of Maximum Amplitude Compared to Baseline

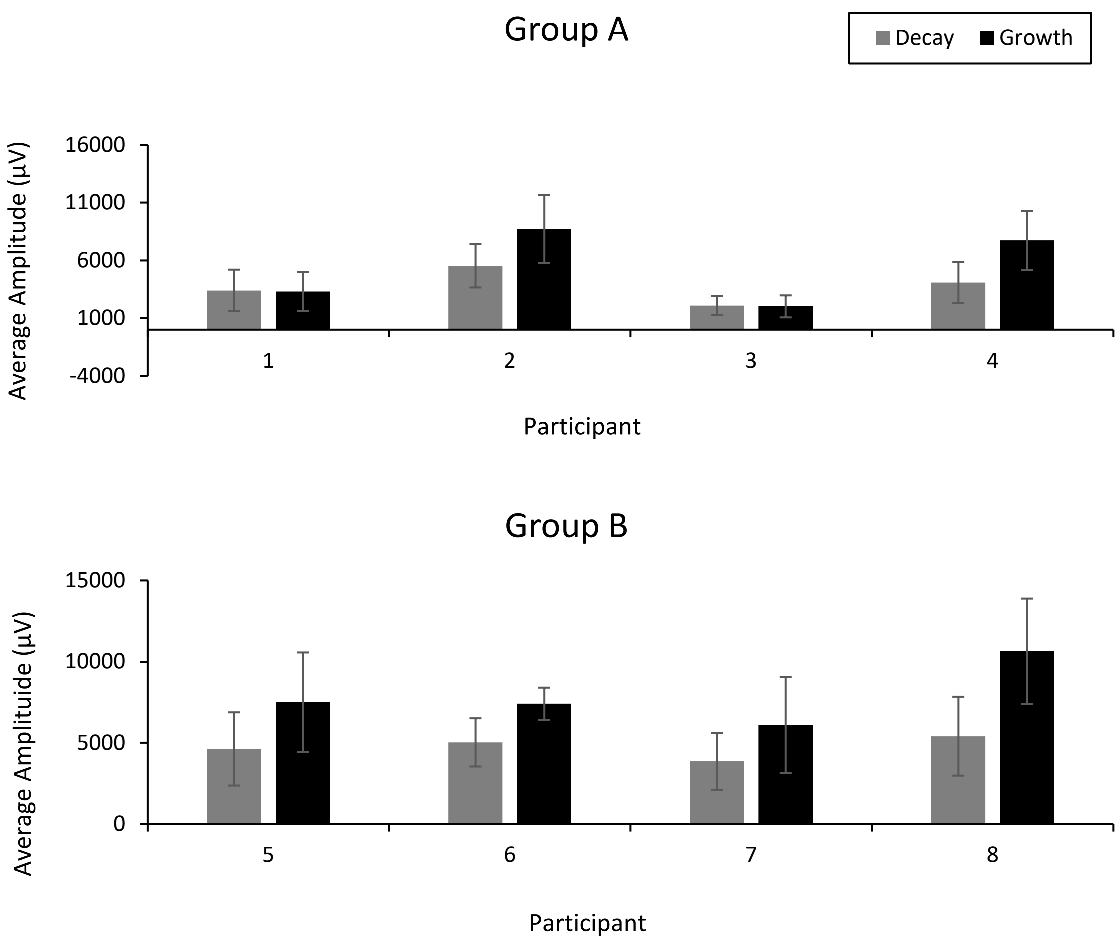


Note. The two graphs depict how the highest amplitude was achieved by participants within each condition compared to their corresponding baseline value.

Figure 4 shows the average amplitude for the Decay and Growth conditions. The Growth condition has higher average values than the Decay condition for six of eight individuals. From Group A, Participants 1 and 3 showed lower average amplitude within the Growth condition and both values are close to their Decay value. Overall, the overlapping in the standard deviation suggests similar overall work is being done for all but Participants 6 and 8.

Figure 4

Average Amplitude of Each Participant



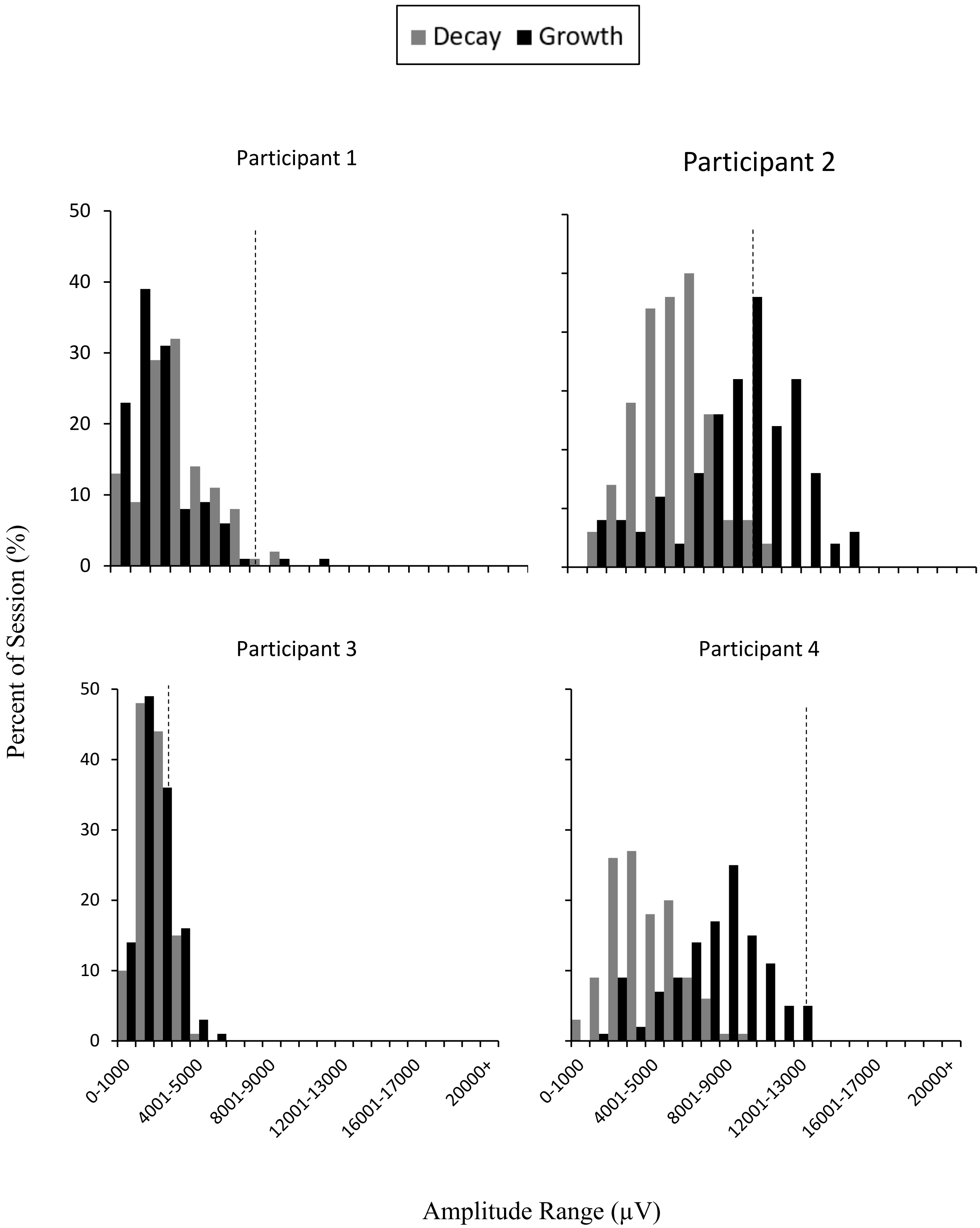
Note. Group A and B's average amplitude are juxtaposed between their Decay and Growth conditions.

Figure 5 shows a binning of microvolt values from each condition into a histogram. Each bin has a width of 1000 µV, with an overall range of 0 to 20,000 µV. All eight participants show a right-skew in the amplitude distribution for the Decay condition. Besides Participant 1 and 3, the other individuals show an opposite, left-skewed pattern in the Growth condition. A majority of the Decay amplitudes remain below the baseline value whereas the Growth amplitudes are occasionally higher.

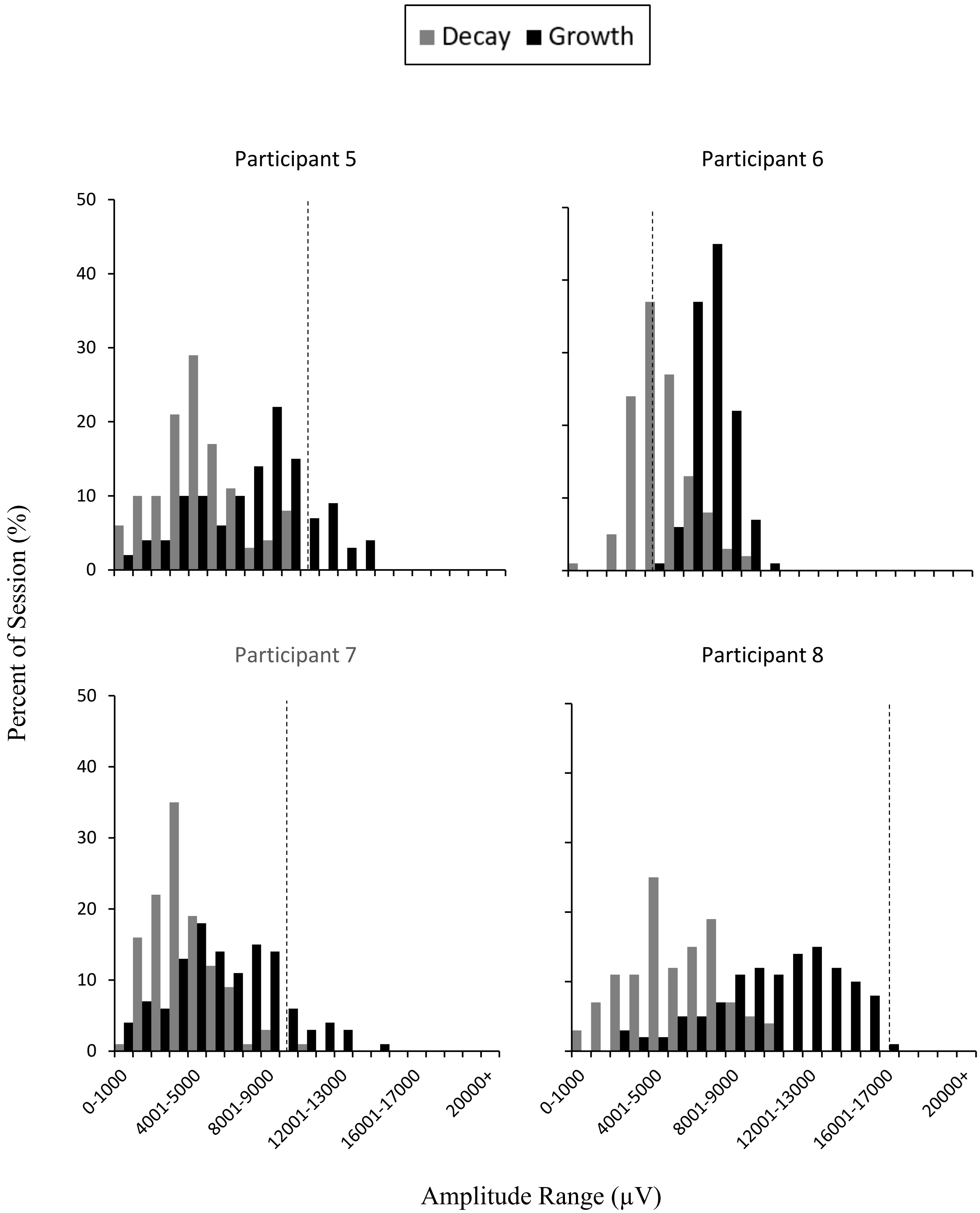
Figure 5

Histogram of Amplitudes with A Baseline Reference

Group A



Group B



Note. The 8 histograms demonstrate the distribution of amplitudes for each participant across an entire session. A dotted line indicates the baseline value from Table 2.

Discussion

The knee is a pinnacle component of our bodies that allows us to get around. We use it on a daily basis, and that constant usage brings an elevated risk of injury. The VMO muscle, a quadricep that helps the knee function, can be strengthened to aid those who are recovering from injury. Biofeeback and sEMG have been implemented as reliable techniques to help with muscle rehabilitation. sEMG works as a measuring system while biofeedback works as a vehicle for reinforcement. Numerous studies focusing on knee rehabilitation used discrete schedules of reinforcement, which differed from typical daily contingencies. Most of our everyday behaviors resemble that of a conjugate schedule of reinforcement where the amount of reinforcement is proportional to a specified property of the response. Thus, the recreation of a similar nonlinear, conjugate system with respect to VMO activation might improve knee performance and recovery time.

This study arranged a relation between the intensity of the VMO contraction and the amount of reinforcement. Participants experienced three conditions: (1) R-MVIC, (2) decay, and (3) growth. With the R-MVIC test determining a baseline, the Decay condition mainly reinforced weak or moderate responses. The Growth condition targeted the most reinforcement at the strongest contractions.

Results showed that the curvilinear conjugate schedule of reinforcement had an influence on behavior. All participants exceeded their baseline value given their Growth condition, while the Decay was not as consistent. Furthermore, the Decay condition resulted in the majority of contractions below the baseline value, promoting weaker responses by providing the most reinforcement there. Although Figure 4 further shows the higher amplitudes in the Growth, both conditions are likely to generate comparable amount of work. Higher peaks in the Growth condition commonly proceed with a sharp decrease in amplitude afterward. The mean thus becomes similar to the Decay, which holds more sustained contractions.

A strength of this project lies in the unexplored use of curvilinear conjugate schedules in the context of muscle contractions. Two schedules have been developed with varying difficulty to reach maximum reinforcement. The Decay condition comprises an initial ease, heavily reinforcing the smaller amplitudes. This may prove useful for individuals trying to regain their mobility, specifically those in rehabilitation and physical therapy. The Growth condition reserves its reinforcement for the stronger VMO contractions, indicating viability for those wanting to increase their baseline amplitudes even further. For instance, enhancing performance is beneficial for athletes who are regularly performing at their peak. Nonetheless, future studies could further optimize the curvilinear relation of the conjugate schedule, refining the required effort to completely fill the progression bar depending on the goals of the intervention.

One weakness was that the lack of a linear condition to compare with the curvilinear relations. A linear condition provides a framework to conclude with confidence if a Decay or Growth condition was more effective. Such exclusion came from possible concerns that the participant would experience muscle fatigue after over 30 VMO contractions. Including a third phase could result in less-than-ideal measurements due to overworking the VMO. Later procedures could incorporate a linear phase by reducing the number of trials across all three conditions.

Another weakness comes from the baseline value obtained from the R-MVIC test. The three extinction trials from which the baseline value was referenced were not always representative of their highest amplitude. A few participants had higher peaks from the three trials prior to the extinction trial. This would exaggerate the improvement from baseline for those individuals with respect to the Decay and Growth conditions. A future direction could incorporate a new strategy for obtaining one's baseline value. On the other hand, a new study may continue to use the R-MVIC condition, but instead utilize a baseline value with the highest amplitude within the set of 4 trials.

Our study has shown that a curvilinear relation of conjugate schedule can significantly shape a response's intensity. Future research endeavors may further refine Equations 1 and 2 to tailor the process to different scenarios. There can be a change to the parameter values from Equations 1 and 2 to better optimize the procedure. Each can be further tailored to a participant's past repertoire, changing as the contractions improve over time. A combination of the Growth and Decay conditions into one phase could also provide valuable outcomes (e.g., a sigmoid function). All in all, this research will help with the accessibility and affordability of physical rehabilitation while coupling behavior analysis and the world of healthcare.

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