Original Article

JER

https://doi.org/10.12965/jer.2448646.323

Journal of Exercise Rehabilitation 2025;21(1):16-24

Effectiveness of proprioceptive neuromuscular facilitation exercise with virtual reality motion capture gaming system and concurrent feedback on early shoulder muscle activation in healthy individuals

Bosco Seongyeol Park*, Jason Verdisco, Matthew Kimball, Aqsa Zuhair, Ayse Ozcan Edeer

Doctor of Physical Therapy Program, Dominican University New York, Orangeburg, NY, USA

This study explores the effect of proprioceptive neuromuscular facilitation (PNF) exercises combined with a virtual reality (VR) motion capture system and concurrent feedback (CF) on early shoulder muscle activation in healthy individuals. Thirty healthy participants sequentially performed three PNF diagonal 2 shoulder exercises: PNF alone, PNF with VR (PNF+VR), and PNF with VR and CF (PNF+VR+CF), with the latter two exercises presented in randomized order. Using wireless surface electromyography and 3-dimensonal (3D) inertial measurement units, the activation of the upper trapezius (UT), lower trapezius (LT), infraspinatus (INF), and serratus anterior (SA) muscles, as well as shoulder flexion, abduction, and external rotation range of motion, were recorded during three exercises. INF and LT muscles were activated earlier in abduction and flexion during PNF+VR and PNF+VR+CF exercises than in PNF alone ($P<0.05$). These muscles were also activated during the early external rotation phase during PNF alone ($P<0.05$). No statistically significant differences were observed in UT and SA muscle activation among PNF alone, PNF+VR, and PNF+VR+CF exercises ($P>0.05$). Integrating VR gaming elements and CF into PNF shoulder exercises may promote early muscle activation, offering a promising approach for advanced rehabilitation strategies that can potentially improve patient outcomes. VR motion capture systems have the potential to transform traditional therapeutic approaches by increasing enjoyment and engagement, which can, in turn, enhance patient motivation and adherence.

Keywords: Proprioceptive neuromuscular facilitation, Virtual reality, Feedback, Electromyography, Muscle activation, Shoulder

INTRODUCTION

Proprioceptive neuromuscular facilitation (PNF) exercises are widely recognized in physical therapy and rehabilitation for enhancing muscle strength, coordination, and range of motion (ROM) in individuals with musculoskeletal and neurological conditions (Witt et al., 2011; Zaidi et al., 2023). Recent advancements, such as virtual reality (VR) motion capture systems, offer the potential to enhance PNF efficacy by providing real-time movement feedback, which is gaining traction as a tool to improve patient outcomes (Fuertes Muñoz et al., 2019).

Integrating PNF with VR's interactive gaming elements enables therapists to create engaging rehabilitation programs. These interactive environments can foster patient motivation and adherence while facilitating motor learning and skill acquisition (Fuertes Muñoz et al., 2019). Studies have shown that markerless motion capture systems, such as Microsoft Kinect, improve rehabilitation outcomes and are associated with high levels of patient enjoyment and engagement (Knippenberg et al., 2017).

The PNF diagonal 2 (D2) shoulder flexion exercise plays a crucial role in activating shoulder muscles like the serratus anterior (SA), infraspinatus (INF), and the upper trapezius (UT) and lower trapezius (LT), which are essential for functional activities and sports performance. This pattern integrates shoulder flexion, abduction, and external rotation, highlighting its importance in rehabilitation (Youdas et al., 2012).

*Corresponding author: Bosco Seongyeol Park https://orcid.org/0009-0004-7889-1242
Doctor of Physical Therapy Program, Dominican University New York,
470 Western Highway South, Orangeburg, NY 10962, USA
Email: boscoparkpt@gmail.com
Received: November 4, 2024 / Revised: December 5, 2024 / Accepted: December 11, 2024

https://www.e-jer.org
pISSN 2288-176X
eISSN 2288-1778

Research on Kinect-based platforms like KineActiv (AraHealth, Teruel, Spain) has demonstrated the usability, enjoyment, and reliability of these systems in upper limb rehabilitation, along with accurate tracking and measurement of limb motions. Such platforms are promising for strengthening upper limb muscles and increasing ROM, with potential benefits for motor learning and activities of daily living (Fuertes Muñoz et al., 2019).

Concurrent feedback (CF) has been explored as a potential enhancement to rehabilitation but requires further investigation when combined with motion capture. Some studies suggest CF benefits performance (Vitali et al., 2021), while others indicate mixed effectiveness compared to alternative feedback types (Huang et al., 2012). This study seeks to address this knowledge gap by evaluating CF combined with VR motion capture on rehabilitation outcomes.

Surface electromyography (EMG) is valuable for understanding muscle activation patterns during the early stages of ROM rehabilitation. EMG systems allow real-time monitoring of muscle activity, aiding in assessing timing, intensity, and coordination, which supports neuromuscular diagnosis, rehabilitation tracking, and athletic performance optimization (Campanini et al., 2020).

This study aimed to investigate the immediate effect of PNF with a VR motion capture system and CF on early shoulder muscle activation and ROM in healthy individuals. The hypothesis was that the PNF D2 shoulder exercise combined with VR and CF would result in earlier shoulder muscle activation compared to PNF alone.

MATERIALS AND METHODS

Study design

This study used a single-group repeated measures design to examine the effects of PNF exercises combined with VR and CF on early shoulder muscle activation in healthy individuals.

Participants

A total of 32 healthy adults were initially tested for this study. However, due to technical issues during data collection, data from two participants were excluded, resulting in a final sample size of 30 participants (14 males and 16 females; mean age 26.2±3.9 years) (Table 1). Participants were recruited using convenience sampling. Inclusion criteria required participants to be 18–45 years old and able to perform the PNF D2 shoulder flexion exercise. Exclusion criteria included any recent shoulder injuries in the dominant arm within the past three months, such as pain in the scapular region, rotator cuff tear, shoulder dislocation, instability, frozen shoulder, fracture, or chronic neck pain (Youdas et al., 2012). This study received ethical approval from the Institutional Review Board (IRB) at Dominican University New York as minimal-risk research (IRB #2023-0322-01), and all participants provided informed consent.

Table 1. Demographic characteristics of study participant

Characteristic	Value
Age (yr)	26.2±3.9
Height (cm)	169.6±10.0
Weight (kg)	74.2±16.3
Gender	
Male	14 (46.7)
Female	16 (53.3)
Physical activity type	
Cardio	4 (13.3)
Weights	5 (16.7)
Mixed	20 (66.7)
None	1 (3.3)
Other	0 (0)
Days with 30+ minutes of physical activity per week	
0	1 (3.3)
1–3	17 (56.7)
4–6	11 (36.7)
7	1 (3.3)
Upper body exercise frequency per week	
0	2 (6.7)
1–3	24 (80)
4–6	4 (13.3)
7	0 (0)
Arm dominance	
Right	28 (93.3)
Left	2 (6.7)

Values are presented as mean±standard deviation or number (%).
Cardio, aerobic exercise.

Materials

To measure shoulder muscle activation and ROM, we used the NORAXON 3D Motion Capture system with Ultium EMG sensors and Ultium Motion ROM sensors (Noraxon Inc., Scottsdale, AZ, USA). The system provided high-reliability data on muscle activity (intraclass correlation=0.87–0.98) (Grime et al., 2018). Ultium EMG sensors captured maximum voluntary contraction (MVC) and %MVC during three interventions, while Ultium Motion ROM sensors recorded shoulder movements across flexion, abduction, and external rotation. Data was collected using MyoMUSCLE and MyoMOTION software (Noraxon Inc.).

Xbox Kinect (Microsoft Corpo., Redmond, WA, USA) and Be-

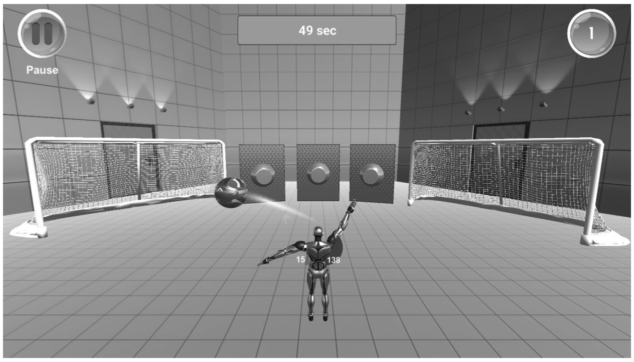

Fig. 1. Gameplay interface of the BeCure software's U-ball video game.

Cure game software (BeCure, Istanbul, Turkey) facilitated VR exercises. The U-Ball game displayed targets on-screen, which participants struck using the PNF D2 shoulder flexion pattern on the dominant arm (Fig. 1). Visual feedback was provided by an avatar reflecting the participant's movements, although scoring elements were excluded to focus on movement accuracy.

Participants' perceived exertion and engagement were assessed using the Borg rating of perceived exertion and a custom questionnaire evaluating difficulty, confidence, enjoyment, frustration, and boredom (Chen et al., 2002; Chen et al., 2021). For our custom questionnaire 5 questions were selected from the physical activity enjoyment scale (PACES) to assess difficulty, confidence, enjoyment, frustration, and boredom. The selected items included: Difficulty: I find it energizing (0 point) - I find it tiring (7 point), Confidence: It gives me a strong sense of accomplishment (0 point) - It does not give me any sense of accomplishment (7 point), Enjoyment: I enjoy it (0 point) - I hate it (7 point), Frustration: I am very frustrated by it (0 point)-I am not frustrated at all by it (7 point), Boredom: I feel bored (0 point) - I feel interested (7 point). The criterion-related validity of the PACES for light physical activity was reported as r (107) = 0.26, $P < 0.05$, r (107) = 0.26, $P < 0.05$, and its test-retest reliability was reported as r (199) = 0.69, $P < 0.05$, r (199) = 0.69, $P < 0.05$ (Weyland et al., 2024).

Interventions

This study implemented three distinct shoulder muscle activation interventions:

Intervention I (PNF alone): Foundational PNF D2 shoulder flexion exercise, incorporating shoulder flexion, abduction, and external rotation (Fig. 2). This exercise was performed at a metronome-guided pace of 14 beats per minute to establish a consistent baseline and match the U-Ball game's tempo.

Intervention II (PNF+VR): Combined the PNF D2 shoulder flexion exercise with a VR motion capture game (the U-Ball game) (Fuertes Muñoz et al., 2019).

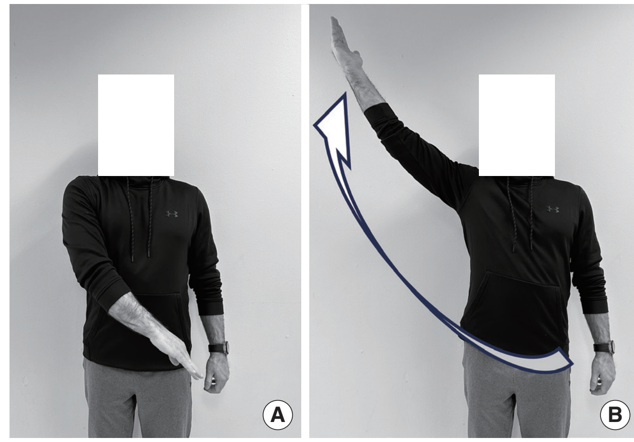

Fig. 2. Demonstration of the proprioceptive neuromuscular facilitation D2 flexion pattern. (A) Starting position with the shoulder in extension, adduction, and internal rotation. (B) Ending position, where the shoulder is brought into flexion, abduction, and external rotation.

Intervention III (PNF+VR+CF): PNF D2 shoulder flexion exercise combined with the U-Ball game and the addition of auditory CF ("Sword"), which referenced the action of unsheathing a sword in a diagonal upward direction (Ludewig et al., 2000; Vitali et al., 2021).

Each intervention lasted 60 seconds, followed by a 2-min rest period, which included survey completion (Fig. 3).

Procedure

Eligibility and informed consent

Researchers screened potential participants for inclusion criteria. Eligible individuals were given a detailed explanation of the study's purpose, interventions, and their role, followed by informed consent. Participants then completed a demographic information form. To protect confidentiality, participants were assigned numerical identifiers, and all identifying information was stored separately from research data in a secure location.

Researchers' roles

Researcher 1 operated the Noraxon equipment and the MyoMUSCLE and MyoMOTION software, ensuring smooth data collection and managing technical operations. Researcher 1 was responsible for extracting data from the raw files, organizing it into an Excel format for analysis, and subsequently forwarding the data to the statistician. Researcher 2 and Researcher 3 collaborated on ROM and EMG sensor placement, confirming accuracy to-

 https://doi.org/10.12965/jer.2448646.323

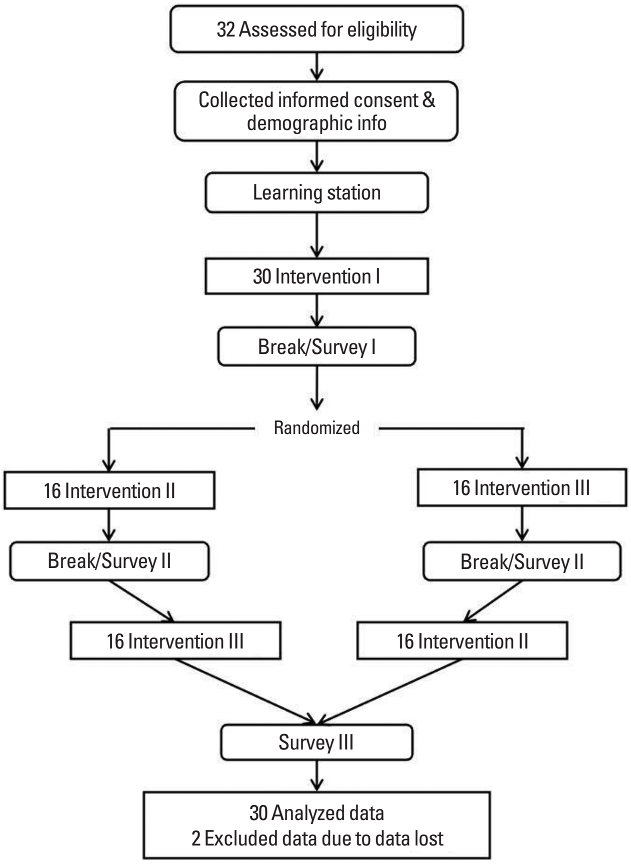

Fig. 3. Flow chart showing the progression of participants through the study phases. Intervention I: PNF alone, Intervention II: PNF+VR, Intervention III: PNF+VR+CF, Survey I, II, III: Borg scale and a customized questionnaire. PNF, proprioceptive neuromuscular facilitation; VR, virtual reality motion capture; CF, concurrent feedback.

gether to maintain data consistency. Researcher 4 guided participants through the informed consent and demographic information forms at the beginning of data collection. Researcher 2 also played a key role in calibration, providing manual resistance for %MVC measurements across targeted muscles and delivering the concurrent verbal cue, "Sword," during intervention III.

EMG and ROM sensor placement

Surface EMG electrodes were placed on the identified motor points of the UT, LT, INF, and SA muscles (Huang et al., 2012; San Juan et al., 2016). ROM sensors were attached to the upper spine (C7/T1), lower spine (T12/L1), and deltoid tuberosity on the participants' dominant arm (Fig. 4). Anatomical landmarks used for sensor placement were confirmed by two researchers for consistency. A male and female researcher assisted with sensor placement to ensure a respectful and comfortable environment.

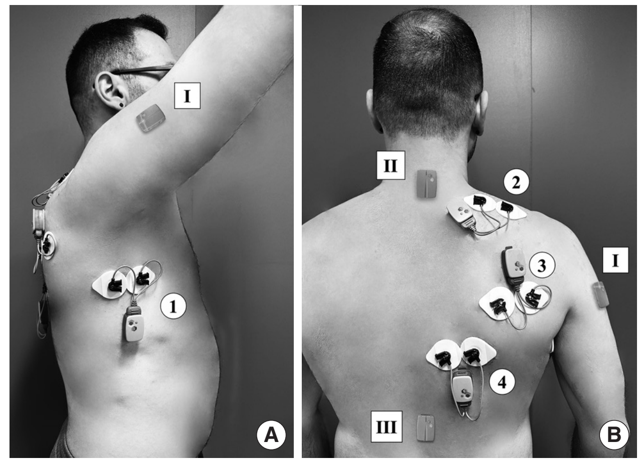

Fig. 4. Placement of surface electromyography (EMG) and range of motion (ROM) sensors. EMG sensors: 1, serratus anterior; 2, upper trapezius; 3, infraspinatus; 4, lower trapezius. ROM sensors: I, deltoid tuberosity (participants' dominant arm); II, upper spine (C7/T1 junction); III, lower spine (T12/L1 junction). (A) Right side view, displaying the placement of an EMG sensor on the serratus anterior (1) and a ROM sensor on the deltoid tuberosity (I). (B) Posterior view, showcasing EMG sensors attached to the upper trapezius (2), infraspinatus (3), and lower trapezius (4), alongside ROM sensors placed on the upper spine (II), lower spine (III), and deltoid tuberosity (I).

Introduction to PNF D2 flexion exercise

At a learning station, participants were introduced to the PNF D2 shoulder flexion exercise and auditory CF via a pre-recorded instructional video. In the video, the researcher explained how the auditory "Sword" CF was utilized (Ludewig et al., 2000; Vitali et al., 2021). Another researcher then provided a live demonstration, allowing participants to practice the pattern and confirm their understanding.

MVC measurements and calibration

Researchers conducted MVC tests for baseline muscle activity (Boettcher et al., 2008; Forbush et al., 2018; Januario et al., 2022). Participants exerted maximum effort against manual resistance applied by the researcher, who was trained to apply consistent resistance across sessions. Participants stood approximately 1.5 meters from the Xbox Kinect camera, aligning with the U-Ball game's software requirements for optimal interaction. ROM sensor calibration took place at this distance, ensuring that participants were positioned correctly for effective motion capture throughout the interventions. Subsequently, muscle activation from UT, LT, SA, and INF muscles and shoulder ROM (flexion, abduction, and external rotation) were monitored and recorded for one minute using the MyoMUSCLE and MyoMOTION software (Noraxon Inc.).

Intervention administration

Participants began with the PNF D2 shoulder exercise at 14 beats per minute, paced by a metronome to match the tempo of the U-Ball game for 1 min. After this initial intervention, participants were given a 2-min break during which they completed a survey (Borg and customized questionnaire) (Chen et al., 2002; Chen et al., 2021). Participants were then randomized for interventions II and III. This randomization involved blindly selecting one of two papers marked II or III, designed to minimize carry-over effects.

Statistical analysis for the collected data

A researcher manually extracted multiple types of raw data from MyoMUSCLE and MyoMOTION software for each participant. This included the ROM at which the maximum single point %MVC occurred for each muscle (UT, LT, INF, SA) across the three exercises. Additionally, the researcher extracted all peak %MVC data points for each muscle during the three planes of motion tested in all exercises, as well as peak ROM data across the three planes (flexion, abduction, and external rotation) of motion for all interventions. This data was compiled into a Microsoft Excel sheet for calculating medians and interquartile ranges (IQRs), as per the guidelines for nonparametric data.

The Shapiro–Wilk test was applied to assess normality. Data with a normal distribution was summarized as mean ± standard deviation, whereas data not following a normal distribution was summarized as median ± IQR. For normally distributed data, Repeated Measures analysis of variance was used, followed by *post hoc* comparisons with Bonferroni P-value adjustments. Data that did not meet normality assumptions were analyzed using the Friedman test, followed by *post hoc* Wilcoxon signed-rank tests. Statistical analyses were conducted using IBM SPSS Statistics ver. 26.0 (IBM Co., Armonk, NY, USA), with the significance level set at $\alpha = 0.05$.

RESULTS

The final sample size included 30 participants (14 males and 16 females; mean age 26.2 ± 3.9 years) who completed all study procedures and were included in the statistical analysis (Table 1).

ROM at maximal muscle activation

In this study, smaller median ROM values were interpreted as indicative of earlier muscle activation where statistically significant differences existed.

There were no statistically significant differences in ROM at which peak muscle activation of the UT occurred during flexion and external rotation across interventions ($P > 0.05$). However, peak muscle activation for the UT during abduction occurred significantly earlier in the PNF+VR group (21.96° ± 23.74°, $P < 0.05$) compared to PNF alone and PNF+VR+CF (Table 2).

For the LT, peak muscle activation during flexion occurred significantly earlier with PNF+VR and PNF+VR+CF (46.47° ± 67.78° and 46.76° ± 78.27°, respectively, $P < 0.05$) than with PNF alone. Similarly, LT peak activation during abduction was significantly earlier in the PNF+VR and PNF+VR+CF groups (39.37° ± 77.08° and 41.98° ± 70.43°, respectively, $P < 0.05$) compared to PNF alone. However, LT peak muscle activation during external rotation occurred significantly sooner in the PNF alone group (17.60° ± 25.50°, $P < 0.05$) than in PNF+VR and PNF+VR+CF (Table 2).

INF peak muscle activation during flexion occurred significantly earlier in the PNF+VR and PNF+VR+CF groups (45.40° ± 55.26° and 36.54° ± 36.82°, respectively, $P < 0.05$) compared to PNF alone. Similarly, INF peak activation during abduction occurred statistically earlier during PNF+VR and PNF+VR+CF (36.84° ± 72.98° and 30.12° ± 43.17°, respectively, $P < 0.05$) compared to PNF alone. However, peak INF activation occurred earlier in the external rotation phase during PNF alone (19.79° ± 27.21°, $P < 0.05$) compared to PNF+VR and PNF+VR+CF (Table 2).

There were no statistically significant differences in ROM for peak SA activation during flexion, abduction, and external rotation across all interventions ($P > 0.05$) (Table 2).

Subjective experience surveys

The Borg Rating of Perceived Exertion scores were interpreted as higher scores indicating greater perceived exertion. Responses from the custom survey were analyzed on a question-by-question basis due to the inclusion of reverse-scored items in the PACES questionnaire, which utilized a 7-point bipolar rating scale. High scores on the custom survey reflected greater difficulty, whereas lower scores indicated higher levels of confidence, enjoyment, frustration, and boredom.

The average Borg Scale scores were statistically significantly higher during the PNF+VR and PNF+VR+CF interventions compared to PNF alone, indicating that the participants perceived greater exertion during the PNF+VR and PNF+VR+CF exercises ($P < 0.05$). However, participants reported no significant differences in perceived difficulty across the three interventions, as indicated by the difficulty question of the custom questionnaire ($P > 0.05$). Participants reported significantly greater confidence levels

 https://doi.org/10.12965/jer.2448646.323

Table 2. Comparison of PNF, PNF+VR, and PNF+VR+CF on shoulder ROM and peak muscle activation

Muscle	ROM	PNF	PNF+VR	PNF+VR+CF	Friedman test	*Post hoc* test
UT	FLEX	39.18±82.24	36.66±17.48	40.24±33.76	χ^2=2.138 *P*=0.358	-
	ABD*	23.03±88.86	21.96±23.74	32.64±50.66	χ^2=9.267 *P*=0.009	PNF=PNF+VR+CF>PNF+VR (highest *P*<0.031)
	ER	42.40±52.74	57.47±25.81	49.72±38.59	χ^2=2.067 *P*=0.370	-
LT	FLEX*	127.73±50.35	46.47±67.78	46.76±78.27	χ^2=20.97 *P*<0.001	PNF>PNF+VR+CF=PNF+VR (highest *P*<0.001)
	ABD*	106.06±15.95	39.37±77.08	41.98±70.43	χ^2=16.80 *P*<0.001	PNF>PNF+VR+CF=PNF+VR (highest *P*<0.001)
	ER*	17.60±25.50	49.85±51.06	46.95±46.07	χ^2=11.667 *P*<0.001	PNF<PNF+VR+CF=PNF+VR (highest *P*=0.001)
INF	FLEX*	107.57±104.34	45.40±55.26	36.54±36.82	χ^2=15.20 *P*=0.001	PNF>PNF+VR>PNF+VR+CF (highest *P*=0.003)
	ABD*	98.28±51.65	36.84±72.98	30.12±43.17	χ^2=6.867 *P*=0.033	PNF>PNF+VR+CF=PNF+VR (highest *P*=0.003)
	ER*	19.79±27.21	48.71±41.92	52.49±27.01	χ^2=15.27 *P*<0.001	PNF<PNF+VR+CF=PNF+VR (highest *P*<0.001)
SA	FLEX	102.63±90.69	69.42±56.32	59.52±75.32	χ^2=4.467 *P*=0.109	-
	ABD	92.48±74.98	76.54±49.39	61.03±57.76	χ^2=1.867 *P*=0.414	-
	ER	33.33±42.04	27.94±37.13	30.16±36.81	χ^2=0.60 *P*=0.755	-

Values are presented as median (interquartile range).
Lower median values are interpreted as earlier muscle activation.
PNF, proprioceptive neuromuscular facilitation; VR, virtual reality motion capture; CF, concurrent feedback; ROM, range of motion; IQR, interquartile range; SD, standard deviation; UT, upper trapezius; LT, lower trapezius; INF, infraspinatus; SA, serratus anterior; FLEX, flexion; ABD, abduction; ER, external rotation.
*$P<0.05$.

Table 3. Comparison of PNF, PNF+VR, and PNF+VR+CF on Borg rating of perceived exertion score and enjoyment, confidence, frustration, boredom, and difficulty questionnaire

Questionnaire	PNF	PNF+VR	PNF+VR+CF	Repeated measures ANOVA	*Post hoc* test
Borg rating of perceived exertion score*	7.10±1.70	8.06±2.55	8.46±2.47	*F*(2,58)=11.15 *P*=0.002	PNF<PNF+VR=PNF+VR+CF
Difficulty: I find it energizing (0 point) - I find it tiring (7 point)*	0.73±1.01	0.86±1.16	1.03±1.42	*F*(2,58)=2.56 *P*=0.250	-
Confidence: It gives me a strong sense of accomplishment (0 point) - It does not give me any sense of accomplishment (7 point)*	1.07±1.50	3.00±2.76	2.84±2.71	*F*(2,58)=11.90 *P*=0.002	PNF<PNF+VR=PNF+VR+CF
Enjoyment: I enjoy it (0 point) - I hate it (7 point)*	3.37±1.03	2.97±1.06	2.87±1.00	*F*(2,58)=4.97 *P*=0.041	PNF>PNF+VR+CF
Frustration: I am very frustrated by it (0 point) - I am not frustrated at all by it (7 point)*	5.94±0.25	5.44±0.85	5.54±0.77	*F*(2,58)=9.27 *P*=0.006	PNF>PNF+VR=PNF+VR+CF
Boredom: I feel bored (0 point) - I feel interested (7 point)*	4.90±1.12	5.54±0.73	5.50±1.00	*F*(2,58)=5.29 *P*=0.002	PNF<PNF+VR

Values are presented as mean±standard deviation.
Scoring: Borg rating of perceived exertion score (no exertion at all, 6, to absolute maximum, 20).
Custom questionnaire: 7-point bipolar rating scale (some items are reverse scored).
PNF, proprioceptive neuromuscular facilitation; VR, virtual reality motion capture; CF, concurrent feedback; ANOVA, analysis of variance.
*$P<0.05$.

when performing the PNF alone compared to PNF+VR and PNF+VR+CF ($P<0.05$). Additionally, the PNF+VR and PNF+VR+CF interventions were rated as significantly more enjoyable than PNF alone ($P<0.05$). Participants also reported significantly higher frustration levels with the PNF+VR and PNF+VR+CF interventions compared to PNF alone, whereas boredom levels were significantly greater during PNF alone than during either VR condition ($P<0.05$ for both) (Table 3).

DISCUSSION

This study investigated the immediate effect of the PNF D2 shoulder flexion exercise with a VR motion capture system and CF on early shoulder muscle activation in healthy individuals aged 18 to 45. The main findings of the study were that the INF and LT muscles were activated significantly earlier during both abduction and flexion phases in the PNF+VR and PNF+VR+CF exercises than in PNF alone ($P<0.05$). However, in PNF alone, INF and LT were active earlier in the external rotation phase ($P<0.05$). To our knowledge, this is the first study to assess muscle activation at specific ranges of motion for UT, LT, INF, and SA muscles during the D2 PNF flexion pattern.

The dynamic motion of the pattern relies on the scapulohumeral rhythm and appropriate firing of the UT, middle trapezius (MT), LT, rhomboids, and SA muscles for movement, and the rotator cuff muscles (supraspinatus, INF, teres minor, and subscapularis) for humeral stability (Witt et al., 2011). We selected the UT, LT, and SA muscles for movement due to their force coupled with the upward rotation of the scapula, while the INF serves as the stabilizer muscle assisting with external rotation to achieve full overhead ROM (Witt et al., 2011). An estimated 7%–36% of the population is affected by dysfunction of the shoulder complex, highlighting the importance of understanding each key muscle's role in dynamic shoulder movement and the impact of PNF, VR, and CF interventions on muscle activation, which may guide healthcare providers in clinical application.

Results demonstrated that the INF and LT muscles were significantly active earlier during abduction and flexion phases in both PNF+VR and PNF+VR+CF, while external rotation showed statistically significant early activation with PNF alone. These findings partially support the research hypothesis, rejecting the null hypothesis that PNF combined with VR and CF would result in earlier muscle activation compared to PNF alone. The finding that PNF alone showed greater early activation during external rotation aligns with prior research suggesting that the transition from internal rotation to external rotation is more stable in the D2 PNF pattern than transitions involving flexion, scaption, or abduction (Morais et al., 2023). It is noteworthy that UT and SA muscles were activated similarly across all interventions.

Since this is the first study comparing early muscle activation during upper extremity exercises using three different interventions, comparisons rely on findings from related individual studies. In examining the effects of CF, our results did not align with Ekblom and Eriksson's findings that CF significantly increased acute muscle activation in the early phase but not the late phase; however, their study focused on knee extensors rather than upper extremity muscles (Ekblom and Eriksson, 2011). Similarly, our results diverge from Vitali et al. (2021), who examined CF's effects on cocontraction in muscles critical to the scapulohumeral rhythm. However, their study evaluated lower extremity muscles (tibialis anterior and medial gastrocnemius).

This study combined VR and CF as Intervention III to evaluate CF's potential added effect on early muscle activation. Findings indicated no significant differences between PNF+VR and PNF+VR+CF in early LT and INF muscle activation. However, UT muscle activation during abduction occurred earlier with PNF+VR than in both PNF alone and PNF+VR+CF. Thus, CF did not benefit the early activation of UT, LT, or INF muscles. Further research is needed to isolate CF's effects on early muscle activation during the PNF flexion exercise.

Based on these findings, patients with limited shoulder ROM in flexion, abduction, or external rotation might benefit from PNF+VR and PNF+VR+CF for flexion and abduction, while PNF alone could be more effective for external rotation. VR gaming may facilitate early muscle activation, which is particularly useful in the early stages of rehabilitation to improve strength in individuals with muscle activation deficits.

Patient compliance with home exercise programs is a significant barrier to successful rehabilitation. In our study, participants perceived PNF+VR and PNF+VR+CF exercises led to greater enjoyment and less boredom than PNF alone. These findings highlight the potential use of VR gaming in rehabilitation, particularly regarding its behavioral, physiological, and motivational effects of gameplay. Interestingly, participants in our study reported significantly greater frustration during the PNF+VR and PNF+VR+CF interventions compared to PNF alone. Frustration is an essential factor in game design, as it can drive engagement through elements such as choice, reward, and goal setting, ultimately enhancing motivation and participation. These findings align with previous studies indicating that marker-free motion capture sys-

https://doi.org/10.12965/jer.2448646.323

tems are more engaging and appealing, which could contribute to increased early muscle activation in the LT and INF during abduction and flexion phases (Lupinacci et al., 2017; Vitali et al., 2021).

Our subjective questionnaire results suggest that VR gaming holds significant potential to transform traditional therapy into a more enjoyable and engaging experience. Task-oriented exercises facilitated by VR gaming not only enhance the training of motor and cognitive skills but also improve patient engagement, enjoyment, and motivation through well-designed game mechanics. When integrated into patient-centered home exercise programs, VR gaming may improve adherence and, ultimately, rehabilitation outcomes.

The average Borg Scale scores were significantly higher during the PNF+VR and PNF+VR+CF interventions compared to PNF alone, indicating greater perceived exertion during these exercises. This finding is noteworthy because participants performed the same PNF D2 shoulder exercise at a consistent speed of 14 beats per minute across all interventions, with the tempo standardized using a metronome. A possible explanation for the increased perceived exertion is the greater cognitive load associated with, the more complex and demanding motor tasks required during the PNF+VR and PNF+VR+CF interventions.

A key limitation of this study is the inclusion of healthy participants, which limits the generalizability of the findings to populations with scapulohumeral dysfunction. Further research is required to evaluate the benefits of VR or VR+CF combined with PNF patterns in populations with such impairments. Additionally, technical challenges were encountered during the study, including data loss from two participants due to software storage capacity issues. Moreover, several participants experienced interruptions with the Kinect sensor during the D2 flexion pattern, which prevented them from viewing their avatar on the screen while performing the task. These technical issues highlight the need to optimize the reliability of VR systems in future studies.

In conclusion, integrating the PNF D2 shoulder flexion exercise with a VR gaming system shows promise as an effective approach for promoting early activation of periscapular muscles. This approach may be particularly beneficial for individuals with restricted shoulder ROM who require targeted muscle activation. CF did not provide any additional benefit in facilitating the early activation of the UT, LT, and INF muscles. The interactive nature of VR-based exercises creates an engaging and motivating environment, which can improve patient adherence and enhance rehabilitation outcomes. Future research should focus on validating these findings in individuals with scapulohumeral dysfunction to establish the clinical efficacy of this intervention further.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

ACKNOWLEDGMENTS

We would like to give special thanks to our statistician Ümit Tural, MD, Research Scientist at the Nathan S. Kline Institute for Psychiatric Research, for his invaluable assistance with our data analysis.

REFERENCES

Boettcher CE, Ginn KA, Cathers I. Standard maximum isometric voluntary contraction tests for normalizing shoulder muscle EMG. J Orthop Res 2008;26:1591-1597.

Campanini I, Disselhorst-Klug C, Rymer WZ, Merletti R. Surface EMG in clinical assessment and neurorehabilitation: barriers limiting its use. Front Neurol 2020;11:934.

Chen C, Weyland S, Fritsch J, Woll A, Niessner C, Burchartz A, Schmidt SCE, Jekauc D. A short version of the physical activity enjoyment scale: development and psychometric properties. Int J Environ Res Public Health 2021;18:11035.

Chen MJ, Fan X, Moe ST. Criterion-related validity of the Borg ratings of perceived exertion scale in healthy individuals: a meta-analysis. J Sports Sci 2002;20:873-899.

Ekblom MM, Eriksson M. Concurrent EMG feedback acutely improves strength and muscle activation. Eur J Appl Physiol 2011;112:1899-1905.

Forbush SW, Bandy WD, Garrison MK, Graves LC, Roberts R. Testing infraspinatus and deltoid muscles with a new technique to decrease deltoid activity during testing using EMG analysis. Int J Sports Phys Ther 2018;13:896-904.

Fuertes Muñoz G, Mollineda RA, Gallardo Casero J, Pla F. A RGBD-based interactive system for gaming-driven rehabilitation of upper limbs. Sensors (Basel) 2019:19:3478.

Grime A, Daines S, Pringle L, Harris T, Hall A. The within-day reliability of scapular and shoulder EMG measurements in asymptomatic individuals during shoulder abduction. N Z J Physiother 2018;46:67-72.

Huang HY, Lin JJ, Guo YL, Wang WT, Chen YJ. EMG biofeedback effectiveness to alter muscle activity pattern and scapular kinematics in subjects with and without shoulder impingement. J Electromyogr Ki-

nesiol 2012;23:267-274.
Januario LB, Cid MM, Zanca GG, Mattiello SM, Oliveira AB. Serratus anterior sEMG - sensor placement and test position for normalization purposes during maximal and submaximal exertions. Med Eng Phys 2022;101:103765.
Knippenberg E, Verbrugghe J, Lamers I, Palmaers S, Timmermans A, Spooren A. Markerless motion capture systems as training devices in neurological rehabilitation: a systematic review of their use, application, target population, and efficacy. J Neuroeng Rehabil 2017;14:61.
Ludewig PM, Cook TM. Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. Phys Ther 2000;80:276-291.
Lupinacci G, Gatti G, Melegari C, Fontana S. Interactive design of patient-oriented video games for rehabilitation: concept and application. Disabil Rehabil Assist Technol 2017;13:234-244.
Morais N, Ferreira J, Gordo J, Vilas-Boas JP, Pascoal AG. A diagonal smovement pattern of arm elevation and depression in overhead throwing athletes: an exploratory kinematic analysis for clinical application. Appl Sci 2023;13:10691.
San Juan JG, Gunderson SR, Kane-Ronning K, Suprak DN. Scapular kinematic is altered after electromyography biofeedback training. J Biomech 2016;49:1881-1886.
Vitali RV, Barone VJ, Ferris J, Stirling LA, Sienko KH. Effects of concurrent and terminal visual feedback on ankle co-contraction in older adults during standing balance. Sensors (Basel) 2021;21:7305.
Weyland S, Kaushal N, Fritsch J, Strauch U, Jekauc D. Validation and invariance testing of the English Short Physical activity enjoyment scale. PLoS One 2024;19:e0313626.
Witt D, Talbott N, Kotowski S. Electromyographic activity of scapular muscles during diagonal patterns using elastic resistance and free weights. Int J Sports Phys Ther 2011;6:322-332.
Youdas JW, Arend DB, Exstrom JM, Helmus TJ, Rozeboom JD, Hollman JH. Comparison of muscle activation levels during arm abduction in the plane of the scapula vs. proprioceptive neuromuscular facilitation upper extremity patterns. J Strength Cond Res 2012;26:1058-1065.
Zaidi S, Ahamad A, Fatima A, Ahmad I, Malhotra D, Al Muslem WH, Abdulaziz S, Nuhmani S. Immediate and long-term effectiveness of proprioceptive neuromuscular facilitation and static stretching on joint range of motion, flexibility, and electromyographic activity of knee muscles in older adults. J Clin Med 2023;12:2610.

https://doi.org/10.12965/jer.2448646.323