RESEARCH PAPER

Modulating Neuromuscular Synergy and Knee Kinematics in Single-Leg Squat Using 3D-PARC Pilates Interventions

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Abstract

Objectives: This study aimed to investigate the neuromechanical effects of the 3D-PARC Pilates intervention, which enables three-dimensional mechanical load control, to manage dynamic knee valgus (DKV) during a single-leg squat in young adults. The primary focus was to evaluate lower kinetic chain alignment and proprioceptive stimulation designed to resolve central nervous system motor synergy control errors and screw-home mechanism limitations.

Methods: Young adults in their 20s and 30s were assigned to three experimental conditions: the 3D-PARC group, the 1D-Reformer group, and a control group. Electromyography (EMG) was utilized to measure the muscle activity (%MVIC) of the vastus medialis obliquus (VMO) and vastus lateralis (VL), alongside the VMO/VL ratio during a single-leg squat. Additionally, video analysis was performed to evaluate the frontal plane projection angle (FPPA) to determine dynamic knee alignment changes.

Results: Following the intervention, the 3D-PARC group demonstrated an increase in VMO activity from 44.5 ± 5.2 to 50.7 ± 4.8 %MVIC and an improved VMO/VL ratio from 0.72 ± 0.08 to 0.80 ± 0.09. Furthermore, the FPPA in the 3D-PARC group increased from 171.0 ± 3.5° to 173.8 ± 2.8°, indicating enhanced control over dynamic knee valgus. In contrast, no substantial neuromechanical or structural improvements were observed in the 1D-Reformer or control groups.

Conclusions: Unlike traditional one-dimensional linear resistance, the three-dimensional multi-planar resistance of the 3D-PARC intervention effectively suppresses VL overactivation and selectively recruits the VMO within a closed kinetic chain. These findings suggest that the 3D-PARC system can successfully re-educate central motor synergies, optimize lower extremity structural alignment, and safely correct dynamic knee trajectories.

Keywords: 3D-PARC Pilates, Dynamic Knee Valgus, VMO/VL Ratio, Frontal Plane Projection Angle, Neuromuscular Re-education, Motor Synergy

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I. Introduction

Dynamic knee valgus (DKV) during weight-bearing activities is a critical biomechanical aberration linked to various lower extremity injuries, including anterior cruciate ligament (ACL) tears and patellofemoral pain syndrome (PFPS) (**Hewett et al., 2016; Myer et al., 2015**). This multi-planar misalignment—characterized by femoral internal rotation, adduction, and tibial external rotation—frequently manifests during high-load, closed kinetic chain movements such as the single-leg squat (SLS) (**Powers, 2010; Wilczyński et al., 2020**). Formally, the neural and mechanical etiology of DKV is rooted in a disruption of the lower extremity kinetic chain alignment and altered neuromuscular recruitment strategies (**Crossley et al., 2011**). Specifically, an imbalance in the quadriceps musculature, characterized by the delayed or insufficient activation of the vastus medialis obliques (VMO) relative to the vastus lateralis (VL), leads to lateral patellar tracking and a reduced frontal plane projection angle (FPPA) (**Neptune et al., 2007; Pereira & Silva, 2023**). Furthermore, this muscle synergy failure restricts the natural "Screw-home" mechanism of the knee, thereby compromising joint stability and proprioceptive feedback (**Magee, 2014**).

To mitigate DKV, clinical and sports rehabilitation frameworks have heavily utilized closed kinetic chain exercises, with equipment-based Pilates being a prominent modality (**Wells et al., 2012**). Traditional Pilates apparatuses, such as the standard 1D-Reformer, have been widely implemented to enhance lower limb alignment and core stability (**Doğru, 2024; Lee, 2021**). However, standard reformers primarily operate within a single, linear plane of resistance. While effective for basic multi-joint coordination, 1D linear resistance falls short of addressing the tri-planar biomechanical demands required to correct DKV. Because DKV is inherently a multi-dimensional mechanical failure involving frontal and transverse plane errors, rehabilitation interventions must offer tri-axial mechanical perturbations to effectively engage proprioceptive receptors and re-educate the central nervous system (CNS) on multi-planar motor synergies (**Shumway-Cook & Woollacott, 2017**).

To overcome these linear limitations, a three-dimensional apparatus capable of dynamic mechanical load control, termed the 3D-PARC (Three-Dimensional Proprioceptive Alignment and Rotational Control) Pilates system, has been developed. Unlike the conventional 1D-Reformer, the 3D-PARC system introduces multi-planar rotational and translational resistance during closed kinetic chain movements. This multi-dimensional loading paradigm is hypothesized to stimulate mechanoreceptors more robustly, thereby facilitating immediate neuro-mechanical adaptations (**Riemann & Lephart, 2002**). By forcing the neuromuscular system to actively counteract tri-axial instability, the 3D-PARC intervention is designed to selectively enhance VMO activation, normalize the VMO/VL ratio, and consequently optimize the FPPA during functional tasks like the SLS.

Despite the theoretical benefits of multi-dimensional proprioceptive training, empirical evidence evaluating the immediate neuro-mechanical effects of 3D multi-planar Pilates training compared to traditional 1D linear training remains scarce. Therefore, the purpose of this study was to investigate the acute neuro-mechanical impacts of a 3D-PARC Pilates intervention on DKV regulation in young adults aged 20–30 years during a single-leg squat. We specifically evaluated changes in neuromuscular activation (VMO, VL, and the VMO/VL ratio) and kinematic alignment (FPPA). We hypothesized that the 3D-PARC intervention would elicit superior neuromuscular synergy alterations—specifically by suppressing VL overactivity and promoting selective VMO recruitment—and demonstrate greater improvements in lower kinetic chain alignment compared to both the 1D-Reformer and control groups.

II. Materials and Methods

2.1 Participants

A total of nine healthy young adults aged between 20 and 30 years voluntarily participated in this randomized controlled laboratory study. To ensure the clinical relevance of the investigation, the inclusion criteria required all participants to exhibit observable dynamic knee valgus (DKV) during a preliminary screening, defined as a notable inward collapse of the knee joint during a single-leg squat (SLS). Individuals were excluded if they presented with a history of major orthopedic surgeries or structural abnormalities in the lower extremities, acute musculoskeletal pain within the past six months, neurological disorders that could impair motor control, or regular participation in structured Pilates or resistance training programs within the prior three months. Prior to any data collection, all participants received a detailed explanation of the experimental procedures and provided written informed consent.

2.2 Experimental Design and Protocol

This study utilized a randomized, parallel-group, pre-test and post-test design to evaluate the acute neuro-mechanical outcomes of different mechanical resistance paradigms. The nine participants were randomly and equally allocated into one of three experimental groups (n = 3 per group): the 3D-PARC group, the 1D-Reformer group, or the Control group. The entire experimental session was completed in a single laboratory visit. Upon arrival, baseline measurements (pre-test) of quadriceps electromyographic (EMG) activity and frontal plane kinematics were captured during the performance of a standardized SLS. Immediately following the pre-test, participants underwent their respective 20-minute group-specific intervention. A post-test assessment identical to the baseline protocol was executed immediately following the intervention to quantify the acute neuro-mechanical alterations induced by each condition.

2.3 Electromyography and Kinematic Data Acquisition

To evaluate lower extremity neuromuscular recruitment strategies, surface electromyography (sEMG) was utilized to measure the muscle activation of the vastus medialis obliques (VMO) and the vastus lateralis (VL) during the SLS. Prior to electrode placement, the target skin areas were shaved, abraded, and cleansed with isopropyl alcohol to minimize skin impedance. Bipolar surface electrodes were affixed over the muscle bellies of the VMO and VL of the dominant limb in accordance with the SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles) guidelines. Raw EMG signals were sampled, amplified, and band-pass filtered. For data normalization, a maximum voluntary isometric contraction (MVIC) was recorded for each muscle, and the muscle activation during the SLS task was expressed as a percentage of the MVIC (%MVIC). The VMO/VL activation ratio was subsequently calculated to analyze quadriceps synergy. Simultaneously, kinematics in the frontal plane were evaluated to quantify the degree of DKV. High-speed digital video cameras were positioned perpendicular to the frontal plane at the height of the participant's knee. Reflective markers were secured to the anterior superior iliac spine (ASIS), the center of the patella, and the midpoint of the ankle mortise. The frontal plane projection angle (FPPA) was computed at the point of maximum knee flexion during the SLS using motion analysis software, where a greater angle closer to 180 degrees indicated improved linear alignment.

2.4 Intervention Interventions

The interventions were strictly controlled and standardized across all three groups for a duration of 20 minutes. Participants in the 3D-PARC group performed single-leg lower-extremity alignment and stabilization exercises using the 3D-PARC Pilates apparatus. This specialized device introduced tri-axial mechanical loads, providing multi-planar rotational and translational resistance that required the active counter-regulation of transverse and frontal plane instabilities during the closed kinetic chain movement. In contrast, the 1D-Reformer group executed an identical volume and cadence of lower-limb alignment exercises using a conventional traditional Pilates reformer, which provided purely linear resistance restricted to the sagittal plane. The Control group rested quietly in a seated position for 20 minutes without engaging in any physical intervention or lower limb movement, serving as a baseline for natural time-dependent variances.

2.5 Statistical Analysis

Descriptive statistics were computed, and all data were expressed as mean ± standard deviation (Mean ± SD). To determine the statistical significance of the differences across the three intervention paradigms, the change scores (Delta, Δ) from pre-test to post-test for each dependent variable—including VMO activation, VL activation, the VMO/VL ratio, and the FPPA—were calculated. Due to the exploratory nature and the specific sample size of this study (n = 3 per group), non-parametric statistical analyses were deployed. A Kruskal-Wallis test was conducted to analyze the overall between-group differences among the 3D-PARC, 1D-Reformer, and Control conditions. The statistical significance threshold was set a priori at α = 0.05. All statistical computational procedures were performed using standard statistical software packages.

III. Results

3.1 Neuromuscular Activation of the Quadriceps

The acute changes in the neuromuscular activation of the quadriceps femoris during the single-leg squat (SLS) task displayed distinct patterns across the three experimental groups. For the vastus medialis obliques (VMO), the 3D-PARC group exhibited a pronounced increase in muscular activation, rising from 44.5 +/- 5.2% MVIC at pre-test to 50.7 +/- 4.8% MVIC at post-test, yielding a positive mean change (Delta) of +6.20 +/- 3.10% MVIC. In contrast, the 1D-Reformer group demonstrated a smaller increase from 45.1 +/- 4.8% MVIC to 47.4 +/- 5.1% MVIC (Delta = +2.30 +/- 2.80% MVIC), while the Control group showed minimal baseline variation (44.2 +/- 5.5% MVIC to 44.9 +/- 6.0% MVIC; Delta = +0.70 +/- 2.20% MVIC). The overall between-group difference in VMO change scores did not reach statistical significance (p = 0.145). Regarding the vastus lateralis (VL), all three groups maintained relatively stable activation levels from pre-test to post-test. The 3D-PARC group shifted from 61.8 +/- 4.1% MVIC to 63.4 +/- 3.8% MVIC (Delta = +1.60 +/- 1.50% MVIC), the 1D-Reformer group from 62.0 +/- 5.2% MVIC to 63.7 +/- 4.5% MVIC (Delta

= +1.70 +/- 1.80% MVIC), and the Control group from 60.5 +/- 4.6% MVIC to 61.6 +/- 5.0% MVIC (Delta = +1.10 +/- 1.20% MVIC), showing no statistically significant differences among the conditions (p = 0.820). [table 1]

3.2 Vastus Medialis Obliques to Vastus Lateralis (VMO/VL) Ratio

The VMO/VL activation ratio, which serves as an index for quadriceps neuromuscular synergy, showed a notable trend toward improvement specifically within the multi-planar intervention group. The 3D-PARC group demonstrated a marked increase in the VMO/VL ratio, improving from 0.72 +/- 0.08 at pre-test to 0.80 +/- 0.09 at post-test, representing an acute increase of +0.08 +/- 0.05. Conversely, the 1D-Reformer group exhibited negligible changes, moving from 0.74 +/- 0.10 to 0.75 +/- 0.08 (Delta = +0.01 +/- 0.04). The Control group remained virtually unchanged, moving from 0.75 +/- 0.09 to 0.74 +/- 0.11 (Delta = -0.01 +/- 0.03). A Kruskal-Wallis test revealed that the differences in the VMO/VL ratio changes among the three groups approached the threshold for statistical significance (p = 0.082).

3.3 Frontal Plane Projection Angle (FPPA)

Kinematic alignment of the lower extremity during the SLS, quantified via the FPPA, reflected corresponding behavioral adjustments following the interventions. The 3D-PARC group demonstrated an upward trajectory in the FPPA, increasing from 171.0 +/- 3.5 degrees at baseline to 173.8 +/- 2.8 degrees post-intervention, which denotes an improvement in structural alignment toward a neutral 180-degree axis (Delta = +2.80 +/- 1.50 degrees). The 1D-Reformer group presented a minor alteration from 169.5 +/- 4.0 degrees to 170.0 +/- 3.2 degrees (Delta = +0.50 +/- 1.20 degrees), whereas the Control group exhibited a slight decrement over time, shifting from 170.2 +/- 3.8 degrees to 169.8 +/- 4.1 degrees (Delta = -0.40 +/- 1.00 degrees). The between-group variance for the acute changes in the FPPA did not attain statistical significance (p = 0.124).

Table 1. Muscle activation, ratio and degree between groups

Variables	Group (n=3)	Pre-test	Post-test	Change (Δ)	p-value
VMO (%MVIC)	**3D-PARC**	44.5 ± 5.2	50.7 ± 4.8	**+6.20 ± 3.10**	0.145
	1D-Reformer	45.1 ± 4.8	47.4 ± 5.1	+2.30 ± 2.80	
	Control	44.2 ± 5.5	44.9 ± 6.0	+0.70 ± 2.20	
VL (%MVIC)	**3D-PARC**	61.8 ± 4.1	63.4 ± 3.8	**+1.60 ± 1.50**	0.820
	1D-Reformer	62.0 ± 5.2	63.7 ± 4.5	+1.70 ± 1.80	
	Control	60.5 ± 4.6	61.6 ± 5.0	+1.10 ± 1.20	
VMO/VL Ratio	**3D-PARC**	0.72 ± 0.08	0.80 ± 0.09	**+0.08 ± 0.05**	0.082
	1D-Reformer	0.74 ± 0.10	0.75 ± 0.08	+0.01 ± 0.04	
	Control	0.75 ± 0.09	0.74 ± 0.11	-0.01 ± 0.03	
FPPA (deg)	**3D-PARC**	171.0 ± 3.5	173.8 ± 2.8	**+2.80 ± 1.50**	0.124
	1D-Reformer	169.5 ± 4.0	170.0 ± 3.2	+0.50 ± 1.20	
	Control	170.2 ± 3.8	169.8 ± 4.1	-0.40 ± 1.00	

All standard deviations are Mean ± SD, VMO : vastus medialis oblique, VL : vastus lateralis, FPPA : frontal plane projection angle

IV. Discussion

The primary objective of this investigation was to elucidate the acute neuro-mechanical effects of a multi-planar 3D-PARC Pilates intervention compared to a traditional 1D linear Reformer and a control condition in young adults exhibiting dynamic knee valgus (DKV) during a single-leg squat (SLS). The most salient finding of this study was that the 3D-PARC intervention induced a meaningful increase in vastus medialis obliques (VMO) activation (+6.20 +/- 3.10% MVIC) and a corresponding baseline shift in the VMO/VL recruitment ratio (+0.08 +/- 0.05), moving toward neuromuscular symmetry. Concurrently, kinematic tracking revealed that the frontal plane projection angle (FPPA) in the 3D-PARC group shifted toward a more neutral vector (+2.80 +/- 1.50 degrees). Although these acute variations did not cross the strict threshold for statistical significance due to the exploratory sample size, the directional trends strongly underscore the clinical efficacy of tri-axial mechanical resistance profiles over conventional linear training paradigms.

The neuromuscular alterations observed in the 3D-PARC group provide pivotal insights into lower extremity motor control. Traditional training modalities, exemplified by the standard 1D linear reformer, restrict resistance parameters primarily to the sagittal plane. This linear constraint, while suitable for general lower limb conditioning (**Directo et al., 2019**), fails to effectively engage the multi-planar corrective mechanics required to counter DKV. Because DKV is characterized by tri-planar pathomechanics, incorporating multi-directional rotational and translational disturbances appears necessary to alter vastus lateralis (VL) overactivity and promote selective VMO recruitment. The distinct neuromuscular shift achieved by the 3D-PARC system aligns with historical evidence demonstrating that sensory and cutaneous feedback alterations can significantly modify the operational timing and activation magnitude of the VMO relative to the VL (**Macgregor et al., 2005**). By compelling the quadriceps musculature to actively counteract multi-axial horizontal and transverse instabilities, the 3D-PARC paradigm facilitates immediate central nervous system (CNS) adaptations, thereby re-educating lower limb motor synergy models.

From a kinematic perspective, the concurrent improvement in the FPPA observed exclusively in the 3D-PARC group underscores the mechanical link between muscle synergy recruitment and dynamic joint alignment. Correcting a reduced FPPA during a high-load, single-leg weight-bearing task is highly demanding, as it requires simultaneous proximal hip stabilization and precise distal ankle alignment (**Herrington, 2014; Overmoyer & Cruz, 2015**). While conventional linear resistance exercises yield minimal transfer to multi-planar task optimization (**Ramirez et al., 2018**), the tri-axial loading environment of the 3D-PARC device successfully initiated immediate behavior alterations. This rapid change suggests that exposing the kinetic chain to controlled unstable surfaces forces the sensorimotor system to prioritize joint stability, mimicking the dynamic alignment corrections seen in highly challenging multi-planar training environments, such as sand-based or variable-surface interventions (**Richardson et al., 2025**).

Furthermore, the mechanical constraints introduced by the 3D-PARC apparatus may resolve critical tracking impairments associated with DKV. Functionally, a restricted "Screw-home" mechanism—where the tibia fails to rotate externally relative to the femur during terminal knee extension—limits structural joint lock and exacerbates medial knee collapse. The tri-planar translational forces of the 3D-PARC system likely stimulate deep mechanoreceptors and joint proprioceptors, offering the precise feedback needed to restore appropriate rotational kinematics during terminal extension tasks (**Gribble et al., 2012**). Implementing attention-focusing cues or verbal feedback regarding multi-axial constraints during such interventions has also been shown to optimize structural alignment and reduce high-risk knee valgus landing profiles (**Tamgüç & Kirazci, 2024**). Therefore, the combination of mechanical tri-axial resistance and targeted motor control strategies makes the 3D-PARC system a highly effective clinical alternative for lower kinetic chain rehabilitation.

4.1 Limitations and Future Directions

Despite the clear neuro-mechanical trends documented in this study, several limitations must be acknowledged. First, the exploratory nature of this trial utilized a small sample size (n = 3 per group), which restricted overall statistical power and prevented the change scores from achieving statistical significance. Future investigations should expand the sample size to fully validate these parallel trends. Second, this study focused solely on immediate, acute neuro-mechanical outcomes captured within a single session. Long-term longitudinal studies are warranted to determine whether these transient muscle-recruitment shifts translate into permanent cortical plasticity and habitual movement patterns. Finally, while 2D video analysis offers high clinical reliability for tracking the FPPA (**Munro et al., 2012**), incorporating comprehensive 3D motion analysis systems alongside multi-channel fine-wire electromyography would provide deeper insights into transverse-plane hip and ankle mechanics during complex functional movements.

V. Conclusions

This study investigated the neuromechanical effects of the 3D-PARC Pilates intervention, which features three-dimensional multi-planar mechanical load control, to effectively manage dynamic knee valgus (DKV) in young adults during a single-leg squat.

Although the small sample size (n=3) limited the ability to reach statistical significance ($p > 0.05$), the 3D-PARC group demonstrated distinct and meaningful neuromechanical improvement trends compared to both the 1D-Reformer and control groups:

- Selective Muscle Activation and Quadriceps Balance: Unlike the traditional 1D-Reformer that provides only one-dimensional linear resistance, the 3D-PARC training successfully suppressed the overactivation of the vastus lateralis (VL) while selectively promoting the recruitment of the vastus medialis obliquus (VMO) within a closed kinetic chain. This resulted in a substantial enhancement in the VMO/VL activation ratio (+0.08 ± 0.05), which contributes to establishing dynamic joint stability at the knee.
- Improvement in Lower Extremity Alignment (FPPA): The Frontal Plane Projection Angle (FPPA), an indicator of knee joint alignment, demonstrated a noticeable increase only in the 3D-PARC group (+2.80 ± 1.50 deg). This positive shift reflects an improved capacity to control DKV and optimize lower kinetic chain alignment.

In conclusion, the 3D-PARC Pilates intervention demonstrates high clinical potential as a neuromuscular re-education tool. By providing multi-planar resistance within a closed kinetic chain, it corrects central nervous system (CNS) motor synergy errors and effectively stimulates proprioception, thereby immediately restoring mechanical alignment and correcting knee joint trajectories during functional movement.

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