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Erhan Secer, Kazım Bayram & Derya Ozer Kaya

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Immediate effects of vibration vs. non-vibration foam rolling on biomechanical and viscoelastic properties of knee flexor and extensor muscles in young male recreational athletes: a randomized, controlled, cross-over study

Erhan Secer [a], Kazım Bayram [b] and Derya Ozer Kaya [c,d]

[a]Vocational School of Health Services, Department of Health Care Services, Manisa Celal Bayar University, Manisa, Türkiye; [b]School of Health Sciences, Department of Physiotherapy and Rehabilitation, Kapadokya University, Nevşehir, Türkiye; [c]Faculty of Health Sciences, Department of Physiotherapy and Rehabilitation, Izmir Katip Celebi University, Izmir, Türkiye; [d]Physiotherapy and Rehabilitation Research and Application Center, Izmir Katip Celebi University, Izmir, Türkiye

ABSTRACT

This study examined the immediate effects of vibration (VFR) and non-vibration foam rolling (FR) on the biomechanical and viscoelastic properties of the knee flexor and extensor muscles. Thirteen young male recreational athletes (mean age: 21.46±1.45 years) completed three conditions: VFR, FR, and control conditions. Assessments were performed pre- and post-test using the MyotonPro. Regarding the knee flexors, no significant effects were observed for muscle tone, stiffness, elasticity, or relaxation time ($p>0.05$). Creep increased similarly in both VFR and FR groups ($p=0.038$). Regarding knee extensors, neither intervention affected muscle tone, elasticity, or relaxation time ($p>0.05$). Stiffness decreased in both groups, with VFR demonstrating greater efficacy compared to FR ($p=0.002$). Creep increased similarly in both the VFR and FR groups ($p=0.016$). Both interventions effectively enhanced the creep of knee flexor and extensor muscles and reduced knee extensor muscle stiffness, whereas VFR demonstrated a superior acute benefit in reducing extensor muscle stiffness.

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Athletes; hamstring muscles; myofascial release; quadriceps muscle

Introduction

Foam rolling (FR) has established itself as a cornerstone of self-myofascial release (SMR), witnessing a rapid integration into the training regimens of both elite competitors and recreational practitioners (Martínez-Aranda et al., 2024). This widespread clinical and athletic adoption is predicated on its bifunctional utility; it serves as a potent ergogenic aid for pre-exercise priming and a therapeutic modality for accelerating post-exertional recuperation across diverse sporting and rehabilitative contexts (De Benito et al., 2019). The proliferation of FR is further underpinned by its pragmatic advantages, specifically its low technical barrier to entry, cost-effectiveness, and temporal efficiency (Wiewelhove et al., 2019). Moreover, its perceived efficacy is bolstered by its conceptual alignment with

CONTACT Erhan Secer erhnscr86@hotmail.com Vocational School of Health Services, Department of Health Care Services, Manisa Celal Bayar University, Uncubozköy Health Campus, Manisa 45000, Turkey

traditional manual massage, a practice long associated with performance optimization and metabolic clearance (Kerautret et al., 2020). Operationally, the FR necessitates the strategic utilization of an individual's body mass to exert compressive forces onto myofascial structures via a foam roller (Chauhan & Telang, 2022). This focal mechanical loading is theorized to trigger instantaneous biomechanical and viscoelastic modulations within the extracellular matrix and optimize interstitial fluid dynamics, consequently facilitating inter-layer sliding and attenuating shear stress across contiguous fascial planes (Schleip et al., 2021).

Building upon the foundations of traditional FR, the field of SMR has undergone significant evolution through the integration of oscillatory stimuli, specifically via vibration foam rolling (VFR) (Park et al., 2021; Secer & Ozer Kaya, 2025). This technological progression leverages the synergy between mechanical friction and exogenous vibration, a combination hypothesized to yield superior physiological outcomes compared to static modalities (Nakamura et al., 2022b). The multi-systemic impact of VFR is largely attributed to the profound stimulation of peripheral mechanoreceptors, including muscle spindles and articular receptors (Yang et al., 2021). Beyond localized tissue manipulation, this intensive afferent input is suggested to facilitate neurophysiological adaptations at the central level via complex neuromuscular pathways (Romero-Moraleda et al., 2019). While these neurophysiological pathways explain the underlying mechanisms of FR and VFR, the objective quantification of their efficacy requires a comprehensive assessment of the properties inherent to skeletal muscle tissue.

The mechanical and viscoelastic properties of skeletal muscle are fundamentally defined by five distinct parameters: muscle tone, stiffness, elasticity, mechanical stress relaxation time and creep (MyotonPro, 2026). Muscle tone serves as a neurogenic indicator of basal tension, reflecting the central nervous system's modulation of motor function through natural oscillation frequency (Agyapong-Badu et al., 2016). Stiffness refers to the tissue's intrinsic resistance to external deformation, as determined by the analysis of damped vibrations (Lettner et al., 2024). While elasticity, governed by collagen fibre architecture, represents the capacity for shape recovery following load dissipation (Herzog, 2019), the mechanical stress relaxation time measures the temporal requirements for the tissue to revert to its undeformed state (Guduru et al., 2022). Finally, creep quantifies the progressive strain accumulation under sustained loading, serving as a critical index of the tissue's structural viscoelastic response (Wu et al., 2022). While these metrics provide a standardized profile of tissue health, their clinical and athletic significance is most profoundly realized when examined within the context of the primary muscle groups responsible for locomotion and joint stability.

The knee extensor and flexor muscle groups form the fundamental biomechanical and viscoelastic framework that governs the athletic potential (Maffiuletti et al., 2016; Turner & Jeffreys, 2010). Rather than mere mechanical drivers, these muscles function as a sophisticated biological system that balances force production, joint stabilization, and injury resilience (Kukić et al., 2022). This dynamic interplay is the primary determinant of explosive power and movement quality. Biomechanically, the importance of these groups is most evident during high-velocity manoeuvres: extensors drive vertical jumps and sprint acceleration, while flexors serve as a critical deceleration mechanism to prevent hyperextension (Bencke et al., 2023; Harper et al., 2022). Furthermore, their biomechanical and viscoelastic properties dictate neuromuscular efficiency and metabolic economy (Burns et al., 2020). For long-term athletic sustainability, these muscles must not only possess absolute strength but also demonstrate biomechanical and viscoelastic adaptations to specific dynamic demands, optimizing the stretch-shortening cycle and mitigating injury risk.

The use of FR and VFR has become a staple in athletic recovery and performance enhancement; however, their precise impact on the biomechanical and viscoelastic properties of muscle tissue remains a subject of significant debate. Glänzel et al. (2023) suggest that conducting further high-quality methodological research would be beneficial for a better understanding of how these interventions influence muscle stiffness and related mechanical parameters. Current literature reveals a lack of consensus regarding the effects of FR on muscle tone, stiffness, and elasticity. For the knee extensors, Baumgart et al. (2019) and Schroeder et al. (2021) reported significant reductions in stiffness following FR. Conversely, Sezik et al. (2024) and Schroeder et al. (2019) found that while FR might decrease muscle tone, it fails to alter stiffness or elasticity significantly. This inconsistency extends to the gastrocnemius, where Chang et al. (2021) observed reduced stiffness, while Nakamura et al. (2021) reported no effect even with applications exceeding 90 s. Notably, for the knee flexors, recent studies by Ağaoğlu et al. (2024), Dębski et al. (2025), and Rodoplu et al. (2025) consistently indicate that FR has no significant effect on biomechanical properties, regardless of density or duration, suggesting that the posterior chain may respond differently to mechanical pressure than the anterior chain. VFR introduces an additional mechanical stimulus that may bypass the limitations of traditional rolling. Nakamura et al. (2022b) and Choi and Lee (2021) demonstrated that VFR (ranging from 30 to 48 Hz) is more effective than standard FR in reducing stiffness in the plantar flexors and upper trapezius. However, Wu et al. (2026) argued that 120 s of VFR and FR produce similar effects on major lower limb muscles. These conflicting results underscore the need to investigate whether the addition of vibration provides a superior acute benefit for the complex architecture of the knee flexor and extensor muscles. A significant limitation in the existing body of research is the disproportionate focus on biomechanical properties (muscle tone, stiffness, and elasticity) while neglecting the viscoelastic properties of the muscle, such as mechanical stress relaxation time and creep. While Szajkowski et al. (2025) recently identified that visco-elastic properties exhibit an inverse correlation with alterations in muscle tone and stiffness, such studies remain remarkably scarce.

Understanding how VFR and FR influence the time-dependent behaviour of muscle tissue is essential, as these factors directly govern the muscle's ability to dissipate energy and resist deformation during athletic movement. Therefore, in light of the general theoretical framework and the current literature, this study aimed to investigate and compare the immediate effects of VFR and FR on biomechanical and viscoelastic properties of the knee flexor and extensor muscles in young male recreational athletes. Furthermore, it was hypothesized that both VFR and FR would have positive influences on these properties compared to baseline; however, VFR was expected to demonstrate superior efficacy over FR in these properties.

Methods

Experimental approach to the problem

A randomized, controlled, cross-over experimental design was implemented to evaluate and compare the immediate effects of VFR versus FR on biomechanical and viscoelastic properties of knee flexor and extensor muscles. In this model, VFR and FR served as the independent variables, while biomechanical and viscoelastic properties of knee flexor and extensor muscles constituted the dependent variables. Assessments were conducted at baseline (pre-test) and immediately following the respective interventions (post-test). To mitigate procedural bias and ensure measurement stability, all dependent variables were assessed in a fixed, standardized sequence across all testing sessions. Rigorous blinding and randomization protocols were employed to safeguard the study's internal validity. Participants were randomly assigned to one of three experimental conditions: VFR, FR, or a control condition. This assignment was made by an independent strength and conditioning coach who remained blinded to the study's specific hypotheses. Furthermore, a double-blind approach was maintained throughout the trial: the primary assessor was blinded to group assignments, and a blinded professional performed the statistical analyses to eliminate any potential for investigative bias.

Ethical considerations

The study protocol received formal ethical clearance from the Manisa Celal Bayar University, Faculty of Medicine, Health Sciences Ethics Committee (Date of Approval: 15 October 2025; Decision No: 3460) and was prospectively archived in the ClinicalTrials.gov database (NCT07414238). In strict accordance with the ethical tenets of the Declaration of Helsinki, all participants were comprehensively briefed on the experimental design, potential risks, and clinical benefits associated with the study. Before the initiation of any procedures, written informed consent was formally secured from each participant, ensuring full transparency and adherence to international ethical standards.

Participants

The required sample size for this study was estimated using G*Power software (version 3.1.9.7; Heinrich Heine University, Düsseldorf, Germany). This power analysis was predicated on a two-way repeated-measures analysis of variance (ANOVA), utilizing previously reported stiffness values for the knee extensors (Sezik et al., 2024). Based on an effect size (ES) of 0.536, a significance level of 0.05 and a statistical power of 0.90, the analysis indicated that a minimum of 13 participants was necessary to detect significant differences. The study population comprised young male recreational athletes (age: 21.46 ± 1.45 years; height: 177.38 ± 4.70 cm; weight: 75.30 ± 7.59 kg; body mass index: 23.94 ± 2.34 kg/m^2; physical activity frequency: 4.84 ± 1.06 days/week). Eligibility criteria required athletes to be between 18 and 25 years of age, to have at least 2 years of experience with FR and demonstrate strict adherence to the American College of Sports Medicine (ACSM) guidelines for regular physical activity. Specifically, participants were included only if they met the threshold for

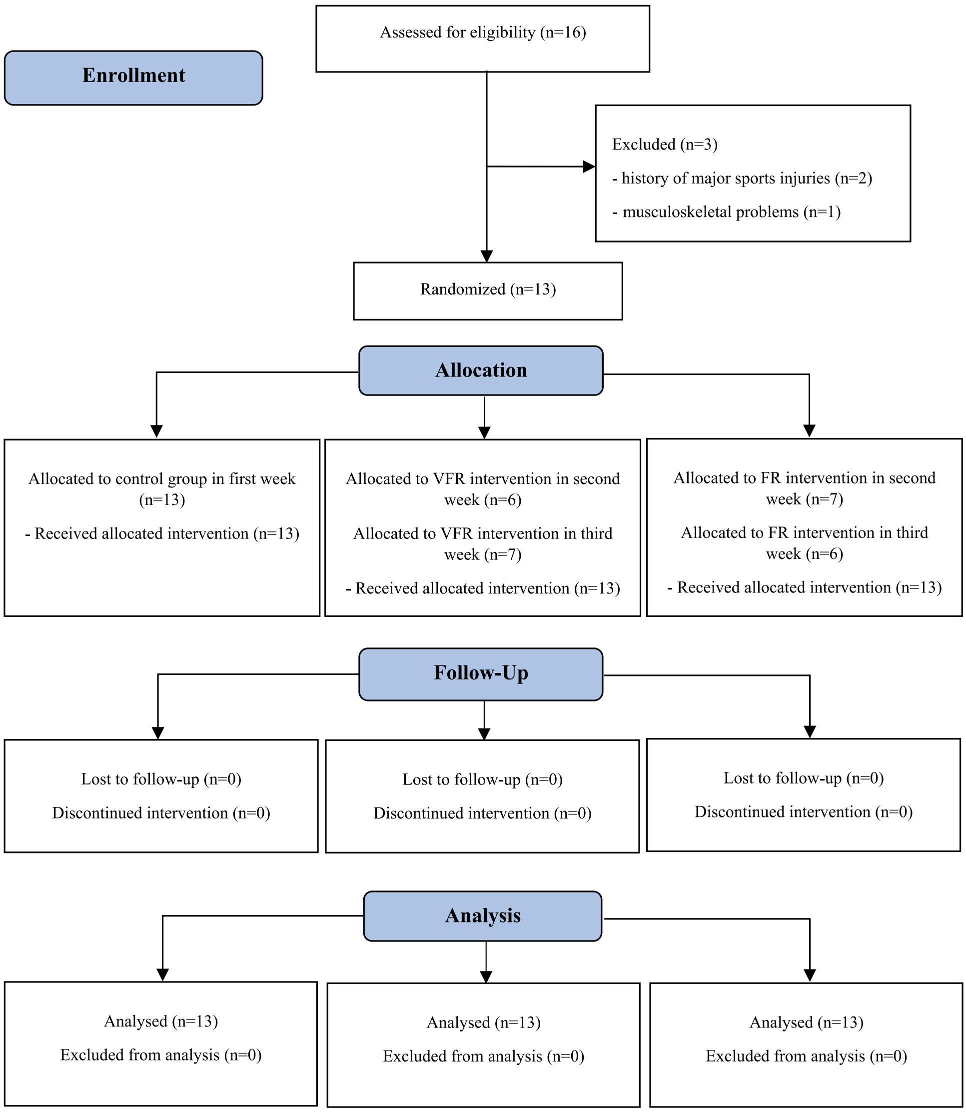

Figure 1. The CONSORT flow diagram of the study.

moderate-intensity aerobic activity (≥30 min on ≥5 days/week) or vigorous-intensity activity (≥20 min on ≥3 days/week) (American College of Sports Medicine, 2025). Exclusion criteria included a history of major sports injuries, defined as surgery or a training hiatus exceeding 6 months ($n = 2$), and pre-existing musculoskeletal disorders such as tendinopathy ($n = 1$) (Secer & Ozer Kaya, 2025). The CONSORT flow diagram of the study is presented in Figure 1.

Procedures

Before data collection, all participants attended a comprehensive one-hour orientation session designed to familiarize them with the experimental interventions and assessment protocols while simultaneously facilitating the recording of baseline anthropometric and demographic data. To ensure environmental consistency and mitigate the influence of external variables, all experimental trials were conducted under standardized physical conditions within a laboratory setting, with participants required to wear identical uniforms and footwear throughout the study. Furthermore, strict lifestyle guidelines were implemented to maintain standardized physiological states; athletes were instructed to refrain from strenuous training and competition, prioritize nocturnal sleep, and maintain adequate hydration and carbohydrate intake for the duration of the investigation (Gallardo-Fuentes et al., 2016). This rigorous control of confounding factors was established to enhance the reliability and internal validity of the dataset.

A randomized, controlled, cross-over experimental design was employed, where each athlete completed three distinct laboratory visits corresponding to VFR, FR, and a control condition. To eliminate potential carry-over or residual effects from previous interventions, a substantial one-week wash-out period was strictly maintained between consecutive sessions, ensuring a full return to the physiological and psychological baseline (Schroeder et al., 2021). Dependent variables for all conditions were assessed at two time points: immediately preceding the intervention (pre-test) and post-intervention (post-test). Specifically, post-test measurements were initiated within a rigorous 60-to-90-second window following the cessation of the FR and VFR protocols to capture acute mechanical and physiological adaptations before their potential dissipation. In the control condition, participants remained in a supine position within a quiet, climate-controlled environment. To account for the potential impact of diurnal variations, all trials were initiated at the same time of day (2:00 PM – 4:00 PM) for each participant, with each testing session efficiently concluded within approximately 10 min. To optimize the detection of acute biomechanical and viscoelastic changes, the experimental protocol was executed independently for each muscle group. Initially, baseline myotonometric assessments (pre-test) were obtained for the knee flexor muscles, followed immediately by the designated intervention (FR or VFR). Post-intervention assessments (post-test) for the knee flexor muscles were completed within the standardized 60-to-90-second window. Following a 3-min standardized rest interval to ensure physiological stabilization and postural transition, the identical procedure, comprising pre-test, intervention, and post-test, was systematically replicated for the knee extensor muscles.

Outcome measures

The biceps femoris (BF) and the rectus femoris (RF) were selected as the primary representative muscles for knee flexion and extension, respectively, due to their anatomical and functional centrality (Mullix et al., 2012). The BF functions as the principal bi-articular muscle of the posterior thigh, essential for hip extension, knee flexion, deceleration, and postural stability (Morin et al., 2015). Given the high eccentric loads it sustains, particularly during sprinting, and its high incidence of injury, evaluating the biomechanical and viscoelastic properties of the BF is critical for assessing injury risk profiles (Yagiz et al., 2024). Conversely, as the sole bi-articular component of the quadriceps femoris group, the RF plays a pivotal role in both hip flexion and knee extension during dynamic activities (Frigo et al., 2020). Its physiological characteristics serve as sensitive indicators of neuromuscular efficiency, while its superficial location makes it an ideal target for accurate, non-invasive assessment.

The biomechanical (muscle tone, stiffness, and elasticity) and viscoelastic properties (mechanical stress relaxation time and creep) of these muscles were measured using the MyotonPro (Myoton AS, Tallinn, Estonia). The MyotonPro (Myoton AS, Tallinn, Estonia) is a widely validated, safe, and non-invasive digital instrument designed for the quantitative assessment of muscle biomechanics and viscoelastic properties (Lettner et al., 2024). Architecturally, the device comprises a central housing unit integrated with a 3 mm diameter depth probe. The measurement sequence begins with the probe exerting a constant pre-pressure of 0.18 N onto the tissue surface. Following this static load, a precise mechanical impulse (0.4 N delivered over 15 ms) is released, imparting a dynamic shear force that induces rapid deformation of the underlying soft biological tissue (Trybulski, Kużdżał, et al., 2024). The resulting damped natural oscillations of the tissue are recorded with high precision as an acceleration signal. This signal is processed concurrently to calculate specific parameters representing the tissue's state of stress, alongside its intrinsic biomechanical and viscoelastic characteristics. All measurement units are derived using established logarithmic algorithms (Lo et al., 2017). In accordance with standardized data collection protocols, the probe is positioned at the designated anatomical site once; however, it executes three successive deformation pulses to ensure the acquisition of robust and reproducible data.

To ensure high spatial standardization for the RF, a reference line was established between the anterior superior iliac spine and the medial border of the patella, with the measurement site defined precisely at the midpoint (Trybulski, Kużdżał, et al., 2024). During RF assessment, subjects were positioned supine, with a 20 cm diameter bolster placed beneath the knees to maintain a consistent joint angle (Trybulski, Stanula, et al., 2024). Conversely, BF evaluations were conducted in the prone position, utilizing an oval cushion under the ankles to facilitate passive hamstring relaxation; subjects were strictly instructed to remain motionless throughout the data acquisition (Kuligowski & Cieślik, 2025). To maintain inter-subject consistency, BF measurements were systematically obtained at the midpoint of the longitudinal axis of the long head (Dębski et al., 2025). All myotonometric measurements were performed on the dominant extremity (Sezik et al., 2024). Extremity dominance was operationally defined and determined by the participants' response to the question: "Which leg would you use to kick a ball at a target?" (van Melick et al., 2017). For each muscle group, two consecutive measurements were performed without interruption. The mean of these two repetitions was subsequently calculated and utilized for statistical analysis to enhance data reliability.

All assessments were performed by a single physiotherapist with over a decade of clinical experience in manual therapy, thereby eliminating inter-rater variability. Following the marking of anatomical landmarks, all procedures strictly adhered to the manufacturer's diagnostic protocols (MyotonPro, 2026). To mitigate technical artefacts, the device's integrated real-time guidance system was employed to monitor and suppress unwanted motion, involuntary muscle contractions, and excessive compressive force. Furthermore, the evaluator stabilized the recording arm by resting the elbow on a level surface to ensure probe perpendicularity. In accordance with established reliability criteria, any measurement set yielding a coefficient of variation (CV) exceeding 3% was deemed unreliable (Muckelt et al., 2022; MyotonPro, 2026). Such data were immediately excluded and re-measured to safeguard the accuracy and integrity of the final myotonometric outcomes. To ensure environmental standardization, all myotonometric assessments were conducted in a climate-controlled laboratory maintained at a constant temperature of 22°C and a relative humidity of 50% (Trybulski, Kużdżał, et al., 2024).

VFR and FR interventions

For both VFR and FR interventions, a vibration foam roller (Vyper 2.0, Hyperice, Irvine, CA, USA), adjustable to frequencies of 48, 60 and 72 Hz was utilized. In alignment with recent systematic evidence suggesting an effective range of 18–48 Hz (Alonso-Calvete et al., 2022), this study adopted the protocol established by Nakamura, Kasahara, et al. (2022a). During the VFR condition, the device was calibrated to a frequency of 48 Hz, falling within the optimal 12–90 Hz spectrum for modulating the musculoskeletal system, with an amplitude of 1.95 mm (Nakamura,et al., 2022b). Conversely, during the FR protocol, the vibration mechanism remained deactivated to serve as a non-vibration control. The interventions targeted the knee flexor and extensor muscle groups. Participants performed three 30 s sets of rolling between the muscle's origin and insertion, utilizing their own body weight as the compressive force, with a 30 s inter-set recovery period. To ensure rigorous standardization, the rolling cadence was synchronized with a metronome at 60 bpm, following established guidelines (Junker & Stöggl, 2019; Kiyono et al., 2022). Players were instructed to execute each longitudinal stroke at a velocity corresponding to two metronome beats per direction. To maintain a consistent physiological stimulus, pressure intensity was monitored and controlled at a target of 7 on a 10-point Numerical Rating Scale (0 = no discomfort; 10 = maximum discomfort) across all conditions (Espí-López et al., 2023).

Statistical analysis

Descriptive data were reported as mean ± standard deviation (SD). The Shapiro–Wilk test was employed to confirm data normality. Baseline homogeneity across the VFR, FR, and control conditions was determined using a one-way ANOVA on all pre-test variables. To evaluate the impact of the interventions, a two-way repeated-measures ANOVA was implemented, utilizing a 3 (Condition: VFR vs. FR vs. Control) × 2 (Time: Pre-test vs. Post-test) factorial design to examine both the main and interaction effects. The magnitude of the effect for partial eta squared (ηp^2) was interpreted according to established criteria as small (<0.01), medium (0.02–0.10) and large (>0.10) (Cohen, 2013; Nakamura, Kasahara, et al., 2022a). In the event of significant interactions or main effects, post-hoc comparisons were conducted using paired t-tests with Bonferroni correction to isolate specific intra-group differences between pre- and post-intervention values. Furthermore, within-group ES were quantified using Cohen's d (d = (M1 − M2)/σpooled), with thresholds categorized as trivial (0.00–0.19), small (0.20–0.49), moderate (0.50–0.79), and large (≥0.80) (Andrade, 2020). All statistical analyses were performed using IBM SPSS Statistics (Standard Concurrent User V 26; IBM Corp., Armonk, NY, USA). The significance level (α) was set at 0.05.

Results

Changes in biomechanical and viscoelastic properties of the knee flexor muscles before and after VFR and FR interventions are presented in Table 1 and Figure 2.

Regarding the knee flexor muscles' biomechanical properties, no significant main effects and group × time interaction effects were observed for muscle tone, stiffness, or elasticity (for muscle tone, T: $p = 0.072$, F = 3.437, $\eta p^2 = 0.087$, G × T: $p = 0.200$, F = 1.682, $\eta p^2 = 0.085$; for stiffness, T: $p = 0.907$, F = 0.014, $\eta p^2 = 0.001$, G × T: $p = 0.838$, F = 0.177, $\eta p^2 = 0.010$; for elasticity, T: $p = 0.700$, F = 0.151 $\eta p^2 = 0.004$, G × T: $p = 0.268$, F = 1.367, $\eta p^2 = 0.071$). Specifically, muscle tone remained stable in the control group (pre-test: 13.08 ± 1.07, post-test: 13.08 ± 1.10, *d*=0.01), while the FR and VFR groups showed a slight reduction (for the FR group, pre-test: 13.13 ± 1.17, post-test: 12.95 ± 1.09, *d*=0.16; for the VFR group, pre-test: 13.14 ± 1.88, post-test: 12.89 ± 1.03, *d*=0.17). Stiffness and elasticity values showed minimal variance across all three groups, with stiffness remaining relatively constant in the control (for stiffness, pre-test: 224.46 ± 53.06, post-test: 226.42 ± 52.94, *d*=0.04; for elasticity, pre-test: 1.06 ± 0.21, post-test: 1.06 ± 0.23, *d*=0.01), FR (for stiffness, pre-test: 220.88 ± 53.76, post-test: 219.50 ± 57.72, *d*=0.02; for elasticity, pre-test: 1.04 ± 0.24, post-test: 1.06 ± 0.25, *d*=0.08), and VFR (for stiffness, pre-test: 222.53 ± 53.81, post-test: 221.00 ± 51.56, *d*=0.03; for elasticity, pre-test: 1.04 ± 0.19, post-test: 1.07 ± 0.22, *d*=0.15) groups.

In terms of the knee flexor muscles' viscoelastic properties, no significant main effects and group × time interaction effects were observed for relaxation time (T: $p = 0.417$, F = 0.675, $\eta p^2 = 0.018$; G × T: $p = 0.636$, F = 0.458, $\eta p^2 = 0.025$). Specifically, values remained stable in the control group (pre-test: 21.32 ± 2.89, post-test: 21.36 ± 2.88, *d*=0.01) and the FR group (pre-test: 21.52 ± 2.92, post-test: 21.40 ± 2.95, *d*=0.04), while the VFR group showed a slight but non-significant decrease (pre-test: 21.29 ± 2.99, post-test: 20.75 ± 2.17, *d*=0.21). For creep, a significant main effect and group × time interaction effect were found (T: $p = 0.021$, F = 245.23, $\eta p^2 = 0.746$, G × T: $p = 0.038$, F = 34.76, $\eta p^2 = 0.651$). While the control group remained stable (pre-test: 1.27 ± 0.16, post-test: 1.28 ± 0.16, *d*=0.06), both the FR group (pre-test: 1.26 ± 0.17, post-test: 1.31 ± 0.15, *d*=0.31) and the VFR group (pre-test: 1.25 ± 0.11, post-test: 1.32 ± 0.17, *d*=0.49) exhibited significant increases in creep values following the interventions.

Changes in biomechanical and viscoelastic properties of the knee extensor muscles before and after VFR and FR interventions are presented in Table 1 and Figure 3.

Regarding the knee extensor muscles' biomechanical properties, no significant main effects and group × time interaction effects were observed for muscle tone and elasticity (for muscle tone, T: $p = 0.233$, F = 1.473, $\eta p^2 = 0.039$, G × T: $p = 0.139$, F = 2.087, $\eta p^2 = 0.104$; for elasticity, T: $p = 0.061$, F = 3.742, $\eta p^2 = 0.094$, G × T: $p = 0.359$, F = 1.055, $\eta p^2 = 0.055$). Specifically, muscle tone showed a slight increase in the control group (pre-test: 11.82 ± 0.74, post-test: 11.91 ± 0.85, *d*=0.11), while the FR and VFR groups showed a slight reduction (for the FR group, pre-test: 12.23 ± 1.29, post-test: 11.74 ± 1.04, *d*=0.42; for the VFR group, pre-test: 12.29 ± 1.28, post-test: 12.16 ± 0.83, *d*=0.12). Elasticity values remained stable in the control group (pre-test: 1.05 ± 0.16, post-test: 1.05 ± 0.19, *d*=0.01), while the FR and VFR groups displayed only minor, non-significant increases (for the FR group, pre-test: 1.03 ± 0.15, post-test: 1.07 ± 0.17, *d*=0.25; for the VFR group, pre-test: 1.04 ± 0.17, post-test: 1.07 ± 0.21, *d*=0.16). For stiffness, a significant main effect and group × time interaction effect were found (T: $p = 0.009$, F = 657.87, $\eta p^2 = 0.953$, G × T: $p = 0.002$, F = 74.45, $\eta p^2 = 0.735$). While the control group showed a slight but non-significant decrease (pre-test: 193.76 ± 36.87, post-test: 192.34 ± 40.56, *d*=0.04), both the FR group (pre-test: 194.46 ± 47.90, post-test: 183.50 ± 44.29, *d*=0.24) and the VFR group

Table 1. Changes (mean ± SD) in biomechanical and viscoelastic properties of the knee flexor and extensor muscles before and after VFR and FR.

	Control Group (n = 13)		FR Group (n = 13)		VFR Group (n = 13)		ANOVA results
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	
KF biomechanical properties							**p-value, F-value, ηp^2**
Muscle tone, (Hz)	13.08 ± 1.07	13.08 ± 1.10	13.13 ± 1.17	12.95 ± 1.09	13.14 ± 1.88	12.89 ± 1.03	T: $p = 0.072$, F = 3.437, $\eta p^2 = 0.087$
		$d = 0.01$		$d = 0.16$		$d = 0.17$	G x T: $p = 0.200$, F = 1.682, $\eta p^2 = 0.085$
Stiffness, (N/m)	224.46 ± 53.06	226.42 ± 52.94	220.88 ± 53.76	219.50 ± 57.72	222.53 ± 53.81	221.00 ± 51.56	T: $p = 0.907$, F = 0.014, $\eta p^2 = 0.001$
		$d = 0.04$		$d = 0.02$		$d = 0.03$	G x T: $p = 0.838$, F = 0.177, $\eta p^2 = 0.010$
Elasticity	1.06 ± 0.21	1.06 ± 0.23	1.04 ± 0.24	1.06 ± 0.25	1.04 ± 0.19	1.07 ± 0.22	T: $p = 0.700$, F = 0.151, $\eta p^2 = 0.004$
		$d = 0.01$		$d = 0.08$		$d = 0.15$	G × T: $p = 0.268$, F = 1.367, $\eta p^2 = 0.071$
KF viscoleastic properties							
Relaxation time, (ms)	21.32 ± 2.89	21.36 ± 2.88	21.52 ± 2.92	21.40 ± 2.95	21.29 ± 2.99	20.75 ± 2.17	T: $p = 0.417$, F = 0.675, $\eta p^2 = 0.018$
		$d = 0.01$		$d = 0.04$		$d = 0.21$	G x T: $p = 0.636$, F = 0.458, $\eta p^2 = 0.025$
Creep	1.27 ± 0.16	1.28 ± 0.16	1.26 ± 0.17	1.31 ± 0.15¶	1.25 ± 0.11	1.32 ± 0.17¶	T: $p = 0.021$, F = 245.23, $\eta p^2 = 0.746$
		$d = 0.06$		$d = 0.31$		$d = 0.49$	G × T: $p = 0.038$, F = 34.76, $\eta p^2 = 0.651$
KE biomechanical properties							
Muscle tone, (Hz)	11.82 ± 0.74	11.91 ± 0.85	12.23 ± 1.29	11.74 ± 1.04	12.29 ± 1.28	12.16 ± 0.83	T: $p = 0.233$, F = 1.473, $\eta p^2 = 0.039$
		$d = 0.11$		d=0.42		$d = 0.12$	G x T: $p = 0.139$, F = 2.087, $\eta p^2 = 0.104$
Stiffness, (N/m)	193.76 ± 36.87	192.34 ± 40.56	194.46 ± 47.90	183.50 ± 44.29¶	193.73 ± 54.76	179.11 ± 37.33¶†	T: $p = 0.009$, F = 657.87, $\eta p^2 = 0.953$
		$d = 0.04$		d=0.24		$d = 0.31$	G × T: $p = 0.002$, F = 74.45, $\eta p^2 = 0.735$
Elasticity	1.05 ± 0.16	1.05 ± 0.19	1.03 ± 0.15	1.07 ± 0.17	1.04 ± 0.17	1.07 ± 0.21	T: $p = 0.061$, F = 3.742, $\eta p^2 = 0.094$
		$d = 0.01$		$d = 0.25$		$d = 0.16$	G x T: $p = 0.359$, F = 1.055, $\eta p^2 = 0.055$
KE viscoleastic properties							
Relaxation time, (ms)	24.25 ± 2.38	24.00 ± 2.60	24.21 ± 2.66	23.97 ± 2.72	23.33 ± 2.29	23.27 ± 3.18	T: $p = 0.194$, F = 1.749, $\eta p^2 = 0.046$
		$d = 0.10$		$d = 0.09$		$d = 0.02$	G x T: $p = 0.356$, F = 1.062, $\eta p^2 = 0.056$
Creep	1.45 ± 0.14	1.44 ± 0.14	1.46 ± 0.14	1.53 ± 0.17¶	1.45 ± 0.17	1.54 ± 0.14¶	T: $p = 0.024$, F = 251.53, $\eta p^2 = 0.524$
		$d = 0.07$		$d = 0.45$		$d = 0.58$	G × T: $p = 0.016$, F = 35.86, $\eta p^2 = 0.364$

FR: Foam rolling; VFR: Vibration foam Rolling; KF: Knee flexor muscles; KE: Knee extensor muscles; The two-way ANOVA results (T: time effect, G x T: group ×time interaction effect; *p*-value, F-value, and partial η^2 (ηp^2) are shown in the right column. ¶: A significantly (p˂0.050) different from the control group. †: A significantly ($p < 0.050$) different from the control and FR groups. *d*: Effect size.

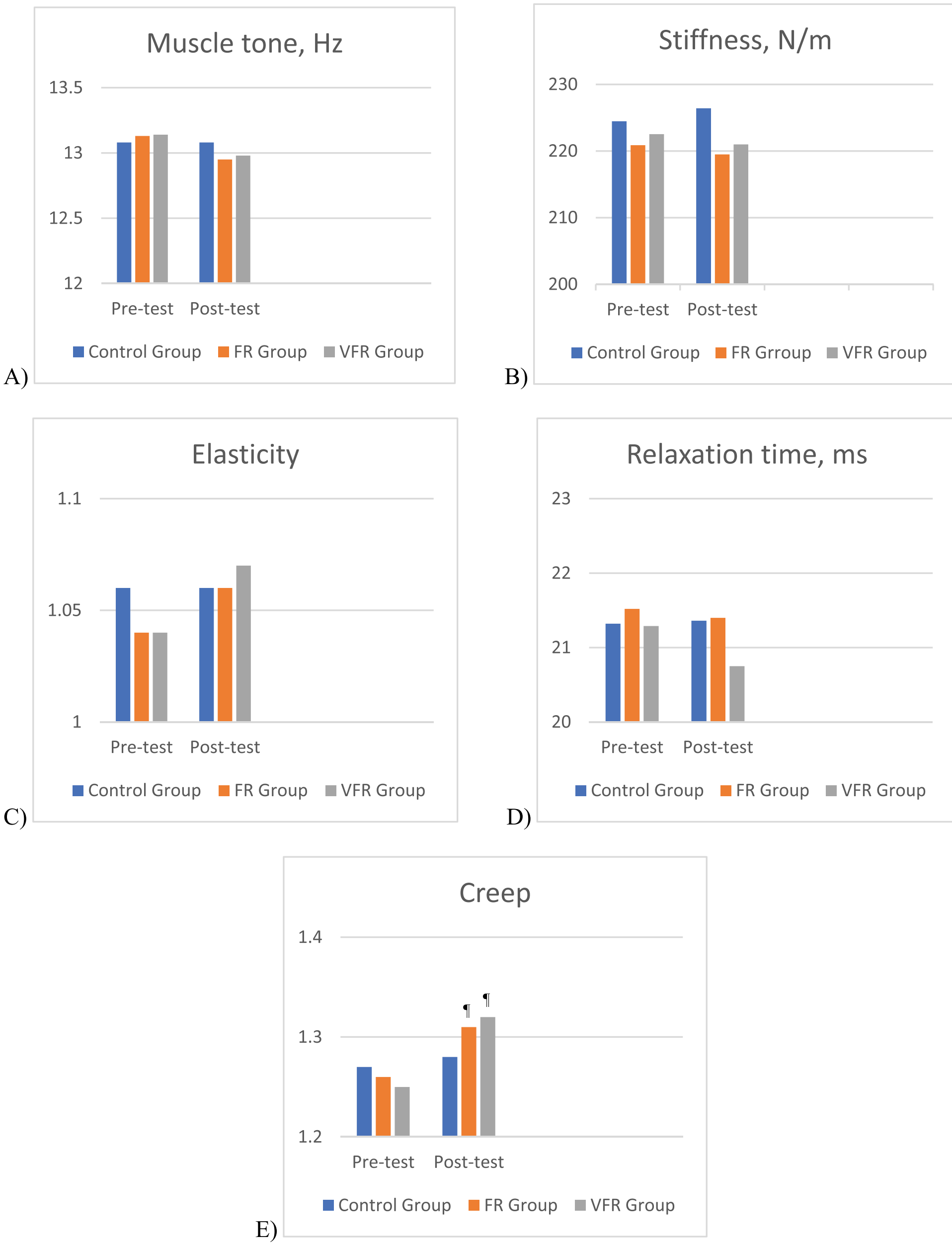

Figure 2. Comparison of (mean ± SD) the biomechanical (muscle tone (A), stiffness (B), elasticity (C)) and viscoelastic (relaxation time (D), creep (E)) properties of the knee flexor muscles changes from pre-test to post-test measurements between the groups. FR: foam rolling; VFR: vibration foam rolling. ¶ :A significantly (p˂0.001 $p < 0.001$) different from the control group.

(pre-test: 193.73 ± 54.76, post-test: 179.11 ± 37.33, d=0.31) exhibited significant decreases in stiffness values following the intervention. Notably, the VFR group showed a more pronounced reduction compared to the FR group.

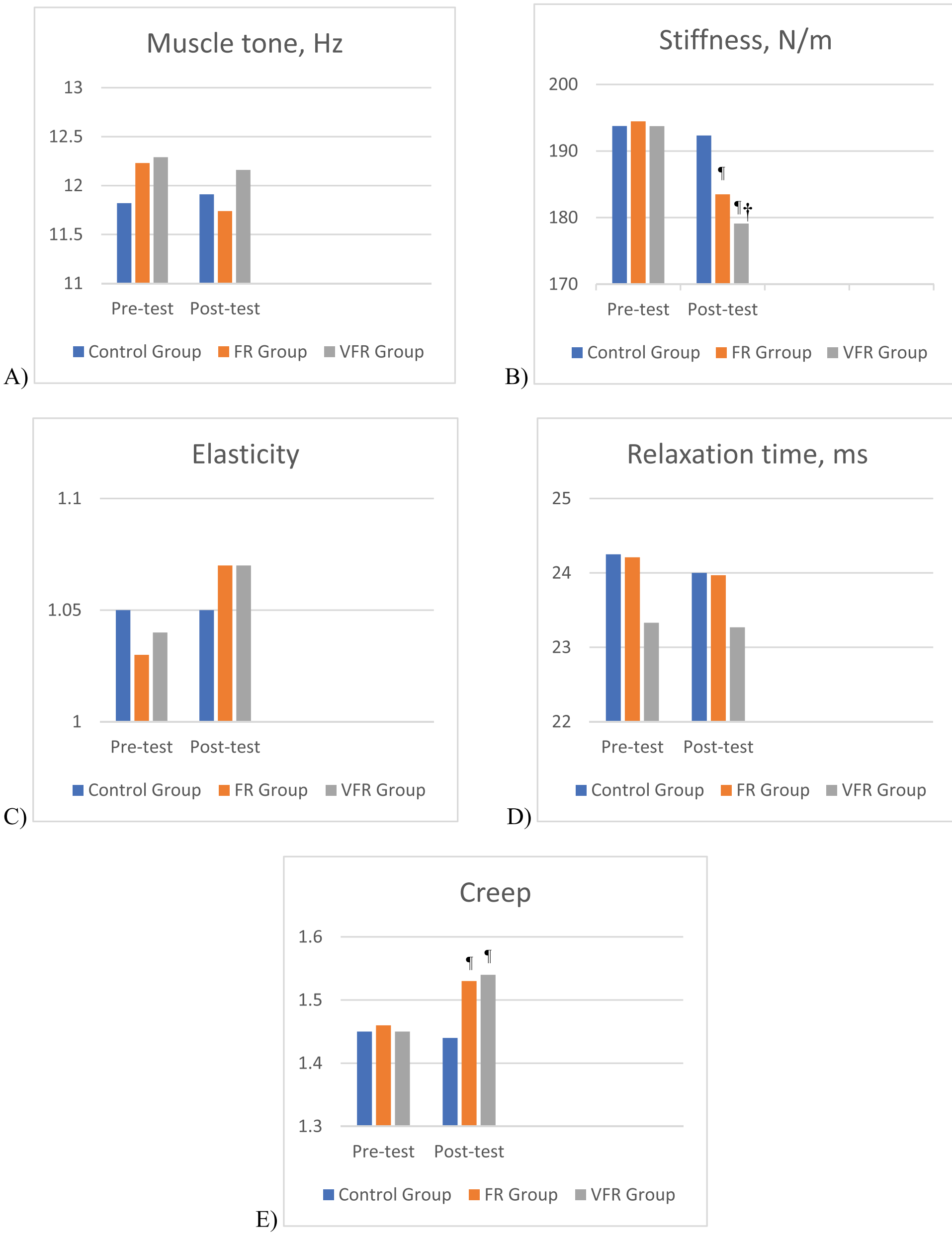

Figure 3. Comparison of (mean ± SD) the biomechanical (muscle tone (A), stiffness (B), elasticity (C)) and viscoelastic (relaxation time (D), creep (E)) properties of the knee extensor muscles changes from pre-test to post-test measurements between the groups. FR: foam rolling; VFR: vibration foam rolling. ¶: A significantly (p˂0.001 $p < 0.001$) different from the control group. †: A significantly (p˂0.001 $p < 0.001$) different from the control and FR groups.

In terms of the knee extensor muscles' viscoelastic properties, no significant main effects and group × time interaction effects were observed for relaxation time (T: $p = 0.194$, $F = 1.749$, $\eta p^2 = 0.046$, G × T: $p = 0.356$, $F = 1.062$, $\eta p^2 = 0.056$). Specifically, values showed a slight but non-significant decrease in the control, FR, and VFR groups (for the control group, pre-test: 24.25 ± 2.38, post-test: 24.00 ± 2.60, *d*=0.10; for the FR group, pre-test: 24.21 ± 2.66, post-test: 23.97 ± 2.72, *d*=0.09; for the VFR group, pre-test: 23.33 ± 2.29, post-test: 23.27 ± 3.18, *d*=0.02). For creep, a significant main effect and group × time interaction effect were found (T: $p = 0.024$, $F = 251.53$, $\eta p^2 = 0.524$, G × T: $p = 0.016$, $F = 35.86$, $\eta p^2 = 0.364$). While the control group remained stable (pre-test: 1.45 ± 0.14, post-test: 1.44 ± 0.14, *d*=0.07), both the FR group (pre-test: 1.46 ± 0.14, post-test: 1.53 ± 0.17, *d*=0.45) and the VFR group (pre-test: 1.45 ± 0.17, post-test: 1.54 ± 0.14, *d*=0.58) exhibited significant increases in creep values following the intervention.

Discussion

This study aimed to investigate and compare the immediate effects of VFR and FR on biomechanical and viscoelastic properties of the knee flexor and extensor muscles in young male recreational athletes. The main findings of this study revealed that both interventions exerted differential effects on the biomechanical and viscoelastic characteristics of the knee flexors and extensor muscles.

Regarding the biomechanical properties of the knee flexor muscles, the results of this study indicated that neither VFR nor FR had any effect on muscle tone, stiffness, or elasticity. These findings are highly consistent with recent literature focusing on the posterior chain. Specifically, our results align with the observations of Ağaoğlu et al. (2024), Dębski et al. (2025), and Rodoplu et al. (2025), who reported that the knee flexors appear resistant to significant biomechanical alterations regardless of the rolling protocol. These consistent observations suggest that while rolling interventions are effective for other physiological outcomes, the intrinsic biomechanical properties of the knee flexors remain remarkably stable. This structural resilience, confirmed across various recent studies, implies that neither VFR nor FR induces acute mechanical disruptions, further solidifying the role of these techniques as safe pre-activity modalities without compromising muscle integrity.

As for the viscoelastic characteristics of the knee flexor muscles, our results indicated that relaxation time was not affected by VFR or FR, whereas creep increased similarly with both methods. This finding is particularly noteworthy in light of the emerging literature on viscoelasticity. Szajkowski et al. (2025) recently reported that viscoelastic properties tend to correlate inversely with changes in muscle tone and stiffness. However, in our study, the knee flexors showed an increase in creep despite no significant changes in stiffness or tone. This suggests that creep, representing the tissue's ability to deform under a constant load, might be a more sensitive marker of acute mechanical changes in the posterior chain than traditional biomechanical parameters. Furthermore, the observation that both VFR and FR increased creep to a similar extent aligns with the perspective of Wu et al. (2026), who argued that 120 s of both rolling modalities produce comparable effects on major lower limb muscles. Specifically, since VFR failed to demonstrate a superior effect on flexor viscoelasticity compared to standard FR, it appears that the viscous component of the posterior chain is more responsive to general mechanical loading than to specific vibration stimuli. These results highlight that, while rolling interventions may not "loosen" the posterior chain in terms of stiffness (Nakamura et al., 2021), they do alter the time-dependent deformation capacity (creep) of the tissue, which could have implications for injury prevention and range of motion.

In terms of the biomechanical properties of the knee extensor muscles, the findings indicated that while neither intervention induced changes in muscle tone or elasticity, both interventions were effective in decreasing stiffness. Furthermore, VFR yielded a significantly greater reduction in stiffness than traditional FR, suggesting a superior acute benefit of vibration stimuli for this muscle group. This outcome aligns with the research of Baumgart et al. (2019) and Schroeder et al. (2021), who reported significant reductions in extensor stiffness following FR. However, our results partially contrast with Sezik et al. (2024) and Schroeder et al. (2019), who found that FR failed to alter stiffness significantly. This discrepancy across the literature likely stems from methodological heterogeneities, such as variations in roller density (shore hardness) and the total volume of mechanical loading applied. Furthermore, VFR yielded a significantly greater reduction in stiffness than traditional FR, suggesting a superior acute benefit of vibration stimuli for this muscle group. This finding strongly supports the evidence provided by Nakamura, et al. (2022b), indicating that the addition of a vibration may be more effective in modulating the structural compliance of the knee extensor muscles. The superior effect of VFR on the extensors, but not the flexors, may be explained by the anatomical orientation and accessibility of the knee extensor muscles. The anterior chain often carries a higher baseline of mechanical stress during weight-bearing activities, potentially making its fascial and muscular components more responsive to the thixotropic effect (the reduction of viscosity under stress) triggered by vibration. The synergistic effect of pressure and high-frequency oscillation likely accelerates the transition of the ground substance from a "gel" to a "sol" state more effectively than pressure alone, specifically in the complex architecture of the knee extensors.

Finally, regarding the viscoelastic properties of the knee extensor muscles, our findings parallel the effects observed in the knee flexors; neither intervention influenced relaxation time, whereas both modalities induced a comparable increase in creep values. This consistency across both muscle groups suggests that while biomechanical stiffness may respond differently to vibration depending on the muscle's anatomical orientation, the viscous deformation capacity (creep) of the lower limb appears to be universally responsive to mechanical rolling. This finding is particularly significant when interpreted alongside the work of Szajkowski et al. (2025), who suggested that changes in viscoelasticity are often coupled with alterations in muscle tone. However, our study demonstrates a dissociation between these parameters in the extensors; although stiffness decreased more significantly after VFR, the increase in creep was identical for both VFR and FR. This indicates that the time-dependent deformation (creep) might be driven primarily by the steady mechanical pressure shared by both protocols, rather than the oscillatory stimulus unique to VFR.

The primary strength of this research lies in its rigorous methodological design and high internal validity. By employing a randomized, controlled, cross-over design, the study effectively minimizes inter-individual variability, as each participant serves as their own control. The implementation of a double-blind approach, where both the primary assessor and the statistical analyst were blinded to group assignments, along with a strict one-week wash-out period, significantly reduces the risk of investigative bias and carry-over effects. Furthermore, the use of the MyotonPro provides an objective, validated, and highly sensitive tool for the quantitative assessment of muscle biomechanics, moving beyond subjective measures often found in manual therapy research. Another significant strength is the comprehensive standardization of the experimental environment and protocols. The study controlled for numerous confounding variables, including diurnal variations by testing at the same time of day, standardized laboratory conditions (temperature and humidity) and strictly monitored lifestyle factors such as sleep and hydration. The intervention itself was highly regulated through the use of a metronome to control rolling cadence and a standardized Numerical Rating Scale to monitor pressure intensity. These measures ensure that the observed changes in viscoelastic and biomechanical properties are directly attributable to the VFR and FR interventions rather than external environmental or procedural factors.

Despite the rigorous design, a notable limitation is the homogeneity of the study population. Because the participants were exclusively young, healthy, male recreational athletes, the findings may not be generalizable (low external validity) to female athletes, sedentary individuals, geriatric populations, or elite professionals. Factors such as gender-specific hormonal profiles and age-related changes in connective tissue architecture could significantly alter the mechanical response to vibration and foam rolling. Furthermore, the study focused solely on acute, immediate effects. While the 60-to-90-second post-test window effectively captures peak physiological adaptations, it does not provide information on the duration of these effects or the long-term chronic adaptations resulting from regular FR or VFR use. Additionally, while myotonometry offers precise data on tissue state, the assessments were conducted in a passive, non-weight-bearing position. This may not fully reflect how changes in muscle stiffness and elasticity translate to dynamic, functional athletic performance, such as explosive power or eccentric deceleration during sport-specific movements. Another limitation of this study is the exclusive use of the 48 Hz frequency setting during the VFR intervention, which precludes an assessment of whether higher vibration intensities (60 Hz or 72 Hz) might yield more significant physiological or performance benefits compared to lower frequencies.

To build upon the findings of the current study, future research should aim to diversify the participant demographic by including female athletes and individuals across different age groups to examine how variations in hormonal profiles and connective tissue architecture influence the response to vibration foam rolling. Additionally, incorporating a longitudinal time-course analysis with multiple follow-up assessments would provide valuable insights into the duration and decay rate of these acute mechanical adaptations. It is also recommended that future trials integrate functional performance metrics, such as vertical jump height or eccentric strength tests, alongside myotonometric measurements to determine the direct impact of altered viscoelasticity on dynamic athletic output. Furthermore, employing objective pressure-monitoring technology instead of relying solely on perceived exertion scales would further enhance the standardization of the mechanical load applied to the soft tissue, ensuring greater precision in comparing different foam rolling modalities. Lastly, future research should implement comparative protocols across the Vyper 2.0's full frequency spectrum (48, 60 and 72 Hz) to better understand the mechanics of VFR, establish a dose–response relationship, and identify the most efficacious VFR settings for different populations.

In summary, the present study suggests that both VFR and FR interventions may influence the viscoelastic properties of the lower limb by increasing creep values while leaving mechanical relaxation time unaffected. Our findings indicate that this increase in creep, an indicator of time-dependent tissue deformation, may emerge as a universal trend across both knee flexor and extensor muscles, regardless of the vibration stimulus. In contrast, the effects on biomechanical properties appear to be muscle-group specific; a reduction in stiffness was observed only in the knee extensors, suggesting that VFR might offer a more pronounced physiological advantage over traditional FR in this particular muscle group.

Notably, neither intervention appeared to induce significant changes in muscle tone, elasticity, and relaxation time. This suggests that foam rolling might primarily influence the viscous component (creep) through a thixotropic effect, rather than directly altering the neural drive or intrinsic elastic characteristics of the myofascial unit. From a practical perspective, VFR application could be prioritized for the anterior chain to enhance mechanical compliance and reduce stiffness. For the posterior chain, traditional FR may be sufficient to affect viscoelastic creep, as the addition of vibration does not appear to provide incremental benefits for hamstring stiffness. Overall, as these modalities can enhance (tissue deformation capacity) without the risk of performance-diminishing "de-toning", they can be considered safe and effective options for pre-activity use.

Author contribution statements

Erhan Secer: Research concept and study design, literature review, data collection, data analysis and interpretation, statistical analyses, writing of the manuscript.

Kazım Bayram: Research concept and study design, data analysis and interpretation, writing of the manuscript.

Derya Ozer Kaya: Research concept and study design, data analysis and interpretation, reviewing/editing a draft of the manuscript.

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ORCID

Erhan Secer http://orcid.org/0000-0002-4476-3785
Kazım Bayram http://orcid.org/0000-0003-4355-3134
Derya Ozer Kaya http://orcid.org/0000-0002-6899-852X

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