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Acute changes in passive muscle stiffness after resistance exercise: A narrative review of effects of program variables

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Abstract

Resistance exercise may empirically be believed to cause acutely increases in passive muscle stiffness in sports and rehabilitation. The acute increase in muscle stiffness limits the joint range of motion (ROM) and may indirectly increase the risk of musculoskeletal injuries and impair athletic performance in some sports events. Thus, a comprehensive understanding of resistance exercise-induced acute changes in passive muscle stiffness is essential in sports and clinical settings. Many studies have investigated acute changes in passive muscle stiffness after resistance exercise. However, no clear consensus has been reached, possibly because of differences in program variables (e.g., contraction mode, exercise ROM, and load) among studies. The present review aimed to provide an overview of the types of resistance exercises with different combinations of program variables that induce acute or insignificant changes in passive muscle stiffness (shear modulus assessed by ultrasound shear wave elastography). This review suggests that 1) muscle stiffness is acutely increased by eccentric-only resistance exercise with a combination of a wide ROM, a high load, and a high volume; 2) muscle stiffness is acutely decreased by eccentric-only resistance exercise with a combination of a wide ROM, long muscle lengths, and a long duration when exercise is performed with a low to moderate load and/or volume; 3) muscle stiffness does not acutely change after concentric-only resistance exercise; and 4) acute changes in stiffness after resistance exercise depend on measured muscles, joint positions, and time points.

Key words: Resistance exercise type, Muscle shear modulus, Shear wave elastography, Methodology

レジスタンスエクササイズ後における受動的筋スティフネスの急性的変化：プログラム変数の影響に関するナラティブレビュー

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スポーツやリハビリテーションでは、経験的に、レジスタンストレーニングは受動的筋スティフネスを急性的に増加させると考えられているかもしれない。筋スティフネスの急性的な増加は、関節可動域(ROM)を制限し、間接的に筋骨格系損傷のリスクを増加させ、いくつかのスポーツ競技における競技パフォーマンスを損なう可能性がある。そのため、スポーツやリハビリテーションの現場において、レジスタンスエクササイズによる受動的筋スティフネスの急性的変化を包括的に理解することは重要である。これまで、多くの研究がレジスタンスエクササイズ後の受動的筋スティフネスの急性的変化について検討している。しかし、プログラム変数（収縮様式、運動 ROM、負荷など）が研究間で異なるためか、明確なコンセンサスは得られていない。本総説は、受動的筋スティフネス(超音波せん断波エラストグラフィにより評価される剛性率)の急性的変化を誘発する（または、誘発しない）レジスタンスエクササイズのプログラム変数の組み合わせについて概観することを目的とした。本総説により、1)広い ROM、高負荷、および高ボリュームの組み合わせによるエキセントリック収縮のみのレジスタンスエクササイズによって、筋スティフネスは急性的に増加すること、2)低から中程度の負荷および/またはボリュームでエクササイズが実施される場合、広い ROM、長い筋長、および長い動作時間の組み合わせによるエキセントリック収縮のみのレジスタンスエクササイズによって、筋スティフネスは急性的に減少すること、3) コンセントリック収縮のみのレジスタンスエクササイズ後に、筋スティフネスは急性的に変化しないこと、4) レジスタンスエクササイズ後における筋スティフネスの急性的変化は、測定する筋、関節肢位、およびタイムポイントによって異なることが示唆された。

Introduction

Resistance training is an effective way to chronically increase muscle strength and size and is thus widely prescribed in the sports and rehabilitation fields. In contrast, a session of resistance exercise may be empirically believed by some practitioners to acutely increase passive muscle stiffness, a determinant of the joint range of motion (ROM).[1,2], possibly due to muscle damage. The limitation of joint ROM has been suggested to increase the risk of musculoskeletal injuries[3,4] and impair athletic performance (e.g., performance of football[5] and volleyball players[6]). Thus, acute increases in passive muscle stiffness by resistance exercise, if any, may increase the risk of musculoskeletal injuries and negatively influence athletic performance in some sports events. From these perspectives, a comprehensive understanding of acute changes in passive muscle stiffness induced by resistance exercise is essential in sports and clinical settings.

Many researchers have investigated acute changes in passive muscle stiffness after resistance exercise. Previous studies reported acute increases,[7–9] decreases,[10–13] and insignificant changes[11,12,14] in the muscle shear modulus (index of passive muscle stiffness). Thus, no clear consensus has been reached regarding resistance exercise-induced acute changes in passive muscle stiffness. These inconsistent results may be related to differences in resistance exercise program variables (e.g., contraction mode, exercise ROM [muscle length], and exercise duration, load, and volume [sets × repetitions] per session) among previous studies based on the following stretching studies. Passive muscle stiffness was reported to be immediately decreased by passive muscle lengthening.[15] Also, the passive muscle stiffness was shown to be decreased only after static stretching with a wide ROM (a long muscle length [80% of maximal joint ROM]), but not with a moderate ROM (moderate muscle lengths [40% or 60% of maximal joint ROM]) in a previous study.[16] Moreover, a larger magnitude of the acute decrease in muscle stiffness was demonstrated after static stretching with a long duration (300 s) per session (duration per repetition × the number of sets × number of repetitions per set) than that with a short duration (120 s) per session.[17] These stretching studies suggest that muscle lengthening over a range of particularly long muscle lengths for long durations is an important factor for inducing acute decreases in passive muscle stiffness. Thus, the types of resistance exercises with different combinations of program variables (e.g., eccentric contraction [muscle lengthening], long muscle lengths, and long duration per session) may influence the magnitude of acute changes in passive muscle stiffness. However, it remains poorly understood how the types of resistance exercises with different combinations of program variables influence passive muscle stiffness.

The present review aimed to provide an overview of the types of resistance exercises with different combinations of program variables that induce acute changes or insignificant changes in passive muscle stiffness. The suggestions of this review may provide helpful information for practitioners to help minimize the risk of musculoskeletal injuries and maintain physical performance.

Literature search

The online databases (PubMed, Web of Science, and Scopus) were searched using combinations of the following terms: Muscle stiffness, Passive tension, Passive condition, Elastography, Shear modulus, Elastic modulus, Shear wave velocity, Ultrasound, Resistance exercise, Resistance training, Strength training, Acute effects, Program variable, and Muscle damage. References of the retrieved articles were also carefully searched to add articles that were not identified electronically. The search was performed in July 2023. The present study included only peer-reviewed original articles written in English. This article did not include running, cycling, and jumping exercises, due to the difficulty in discussing some program variables, such as exercise ROM, load, and muscle length. Meanwhile, the resistance exercise-induced acute changes in muscle shear modulus measured by ultrasound shear wave elastography were shown to be significantly correlated with changes in joint ROM,[12] which influences the risk of musculoskeletal injuries[3,4] and athletic performance.[5,6] In contrast, exercise-induced acute changes in muscle hardness measured by ultrasound strain elastography were reported to be not significantly correlated with changes in joint ROM.[18] Hence, we focused on acute changes in the muscle shear modulus assessed using ultrasound shear wave elastography. Additionally, we also focused on changes occurring within 72 h because resistance exercise-induced changes in the muscle shear modulus were reported to last for at least that time.[9]

Acute increases in passive muscle stiffness after resistance exercise

Several studies have reported acute increases in muscle stiffness after resistance exercise (Table 1).[7–9,14,19–23] Lacourpaille et al.[7] found that the shear moduli of the biceps brachii (proximal, middle, and distal regions) and brachialis (middle region) increased 1 and 48 h after 30 maximal voluntary eccentric contractions of elbow flexion when the shear modulus was measured at 20° of elbow flexion. Agten et al.[19] also demonstrated that the shear wave velocity of the brachialis increased at 15 min (in male participants) and 24 h (in female participants) after 36 eccentric elbow flexions with a load of 90% of one repetition maximum (RM) assessed during concentric elbow flexion. Guilhem et al.[20]

revealed that the shear modulus of the gastrocnemius medialis increased immediately after 300 maximal voluntary eccentric contractions of plantar flexion. Pournot et al.[21] showed an increase in the shear modulus of the biceps brachii immediately and at 5 min after 40 concentric and eccentric elbow flexions with a load of 70% of 1 RM evaluated during concentric elbow flexion. Lacourpaille et al.[14] revealed that the shear moduli of elbow flexors (pooled values of the biceps brachii and brachialis) increased at 30 min after 30 or 60 maximal voluntary eccentric contractions of elbow flexion when the shear moduli were measured at 20° of elbow flexion. They also observed increases in the shear moduli of the knee extensors (pooled values of the rectus femoris, vastus lateralis, and vastus medialis) at 30 min after 75 or 150 maximal voluntary eccentric contractions of knee extension when those shear moduli were assessed at 110° of knee flexion. Similarly, Xu et al.[8] reported an increase in the shear modulus of the rectus femoris immediately and at 48 h after 75 maximal voluntary eccentric contractions of knee extension when the shear modulus was measured at 90° of knee flexion. Ema et al.[9] showed increases in the shear moduli in the proximal and distal regions of the rectus femoris at 24 to 72 h after 100 maximal voluntary eccentric contractions of knee extension at short (seated position) and long (supine position) muscle lengths. They also demonstrated that the magnitude of the increase in the shear modulus of the proximal region in the rectus femoris was greater at 24 h after exercise at long muscle lengths than exercise at short muscle lengths. More recently, Goreau et al.[22] reported increases in the shear moduli of the biceps femoris long head and semitendinosus at 30 min after 75 maximal voluntary eccentric contractions of knee flexion. Similarly, Voglar et al.[23] reported that the shear moduli of the biceps femoris long head and semitendinosus increased immediately after combined eccentric knee flexions (30 maximal voluntary eccentric contractions of knee flexion and 18 repetitions of Nordic hamstring exercise with a body weight load).

In most of the aforementioned studies, resistance exercises consisted of eccentric contractions with a high load (e.g., maximal voluntary contraction and 70%≤ of 1 RM) [24], and a moderate to high volume (30 to 150 repetitions). Additionally, most of the studies adopted a relatively wide exercise ROM. Eccentric exercise with a higher load was shown to induce more severe muscle damage (evaluated by changes in the maximal voluntary torque) than that with a lower load.[25] In addition, eccentric exercise with a higher volume was also reported to cause more severe muscle damage than that with a lower volume.[26] Moreover, resistance exercise, including eccentric contractions with a wide ROM, was reported to induce greater muscle damage than that with a narrow ROM when performed with a high load (80% of 1 RM) and a moderate volume (40 repetitions).[27] Eccentric exercise-induced muscle damage was suggested to acutely increase muscle stiffness, possibly due to rapid perturbations of the intramuscular calcium homeostasis followed by an increase in the number of stable cross-bridges.[7] Thus, eccentric exercise with a combination of a high load, a high volume, and a wide ROM could acutely increase muscle stiffness, due to severe muscle damage. Supportively, Lacourpaille et al.[14] suggested that eccentric exercise with a higher volume greatly increased passive muscle stiffness than exercise with a lower volume when performed with a wide ROM and a high load. Specifically, the magnitude of acute increases in shear moduli of knee extensors was substantially larger after 150 maximal voluntary eccentric contractions (+79.4%) than after 75 eccentric contractions (+26.7%) at 110° to 10° of knee flexion. Meanwhile, less information is available about the acute effects of the load and exercise ROM on passive muscle stiffness in high-volume resistance exercise, which warrants future studies.

Pournot et al.[21] reported an acute increase in the shear modulus of the biceps brachii after concentric and eccentric elbow flexions with a high load (70% of 1 RM), a moderate volume (40 repetitions), and a wide ROM (full elbow flexion to its full extension). As described in our review, eccentric exercise with a combination of a high load, a high volume, and a wide ROM could acutely increase muscle stiffness, due to severe muscle damage. Meanwhile, concentric-only resistance exercise is unlikely to acutely change (decrease or increase) passive muscle stiffness based on the results of some studies[11,13,14]. In the previous study[21], exercise duration per repetition was longer during eccentric phase (5 s) than concentric phase (1 to 2 s). Thus, the relatively longer duration during eccentric phase, rather than during concentric phase, might induce the acute increase in passive muscle stiffness after resistance exercise with a high load and a high volume in the study by Pournot et al.[21] However, there is little evidence of the effects of the difference in exercise duration during concentric and eccentric phases on the acute changes in passive muscle stiffness, which is the future topic.

Acute decreases in passive muscle stiffness after resistance exercise

Some studies have demonstrated acute decreases in muscle stiffness after resistance exercise.[13–16] For example, Chalchat et al.[10] reported a decrease in the shear modulus of the vastus lateralis immediately and at 24 h after 60 maximal isometric contractions of knee extension. Kisilewicz et al.[28] showed a decrease in the shear modulus of the upper trapezius at 24 h after 50 maximal voluntary eccentric contractions of shoulder elevation. Zhi et al.[13] found that the shear modulus of the biceps femoris long head decreased immediately after five maximal voluntary eccentric contractions of knee flexion. Kawama et al.[11] showed that the shear modulus of the semimembranosus decreased immediately after 30 repetitions of eccentric-only stiff-leg deadlift with a load of 60% of the body mass with a wide ROM (0% to 100% of the maximal exercise ROM; 0% = an upright position). Similarly, Kawama et al.[12] observed an immediate decrease in the shear modulus of the semimembranosus after 30 eccentric-only stiff-leg deadlift with a load of 60% of the body mass at long muscle lengths (50% to 100% of the maximal exercise ROM) with a long duration (150 s) per session.

Among the studies cited in the previous paragraph, three studies adopted eccentric-only resistance exercises with a low to moderate load and/or volume[11–13]. As described in the previous section, eccentric resistance exercise with a combination of a high load and a high volume could cause acute increases in passive muscle stiffness, possibly due to severe muscle damage. Thus, a low load and/or a low volume in eccentric-only resistance exercise may be one of the factors to induce an acute decrease in passive muscle stiffness. Meanwhile, Kawama et al.[11] showed that eccentric-only stiff-leg deadlift with a wide ROM (0% to 100% of the maximal exercise ROM) immediately decreased the shear modulus of the semimembranosus, but that with a narrow ROM (0% to 50% of the maximal exercise ROM) did not immediately change its stiffness. Moreover, Kawama et al.[12] showed that eccentric-only stiff-leg deadlift at long muscle lengths (50 to 100% of maximal exercise ROM) with a long duration (150 s) per session immediately decreased the shear modulus of the semimembranosus, whereas the exercise at long muscle lengths with a short duration (60 s) had an insignificant effect. These findings suggest that a wide ROM, long muscle lengths, and a long duration during eccentric-only resistance exercise are key program variables for acutely decreasing passive muscle stiffness when the exercise is performed with a low to moderate load and/or volume.

Contrary to previous studies reporting acute increases in passive muscle stiffness,[7–9,14,19–23)] Kisilewicz et al.[28)] reported an acute decrease in passive muscle stiffness even after eccentric resistance exercise with a high load (maximal voluntary contraction) and a high volume (50 repetitions). Although it is difficult to fully explain the reason for the different results between the previous studies[7–9,14,19–23,28)], the differences in joint positions at which passive muscle stiffness was measured may be related to the discrepancy. Specifically, shear modulus (shear wave velocity) was measured at relatively long muscle lengths in the studies reporting its increase[7–9,19–23)], whereas it appeared to be measured at slack position (no detailed description) in the study by Kisilewicz et al.'s study.[28)] Some studies suggested that acute increases in shear modulus induced by eccentric exercise with a high load and a high volume were observed at relatively long muscle lengths, but not at short muscle lengths, possibly due to the increased sensitivity of muscle fibers to Ca^{2+} increases[7,8)]. Thus, the passive muscle stiffness may not be necessarily acutely increased even after eccentric exercise with a high load and a high volume when the shear modulus (shear wave velocity) is measured at relatively short muscle lengths. This may partly explain the discrepancy between the previous results[7–9,19–23)], although it still remains unclear why the passive stiffness acutely decreased in the study by Kisilewicz et al.[28)]

Meanwhile, Chalchat et al.[10)] observed that passive muscle stiffness acutely decreased after resistance exercise with isometric contractions. They raised some possible factors (e.g., the inability to form sarcomere cross-bridges and increases in the intramuscular temperature) for the acute decrease in passive muscle stiffness following isometric exercise. Owing to limited evidence, little is known about the underlying mechanism(s) of isometric exercise-induced acute decreases in passive muscle stiffness. Further investigations are needed to clarify how isometric exercise acutely influences passive muscle stiffness.

Insignificant acute changes in passive muscle stiffness after resistance exercise

Some studies have reported insignificant acute changes in passive muscle stiffness after resistance exercise.[8,11–14,23] For example, Lacourpaille et al.[14] reported that the shear moduli of elbow flexors (pooled values of the biceps brachii and brachialis) did not change at 30 min after 30 maximal voluntary concentric contractions of elbow flexion. Additionally, Zhi et al.[13] observed an insignificant change in the shear modulus of the biceps femoris long head at 30 to 120 s after five maximal voluntary concentric contractions of knee flexion. Similarly, Kawama et al.[11] showed that the shear moduli of the individual hamstring muscles (biceps femoris long head, semitendinosus, and semimembranosus) did not change at 3 to 60 min after 30 repetitions of concentric-only stiff-leg deadlift with a load of 60% of the body mass with a wide ROM. In all of these studies, concentric-only resistance exercise was adopted while the other program variables (exercise load, volume per session, and ROM [muscle length]) differed among the studies. Thus, concentric-only resistance exercise is unlikely to acutely change (decrease or increase) passive muscle stiffness although the underlying mechanism(s) remains unknown.

Some studies have shown insignificant acute changes in passive muscle stiffness even after eccentric-only resistance exercise.[8,11,12,22,23] Xu et al.[8] reported that the shear modulus of the vastus medialis oblique was unchanged immediately or at 48 h after 75 maximal voluntary eccentric contractions of knee extension. Additionally, Ema et al.[9] reported insignificant changes in shear moduli of the vastus lateralis or vastus medialis at 24 to 72 h after 100 maximal voluntary eccentric contractions of knee extension. Goreau et al.[22] showed that the shear modulus of the semimembranosus was unchanged at 30 min after 75 maximal voluntary eccentric exercises of knee flexion. Similarly, Voglar et al.[23] observed an insignificant change in the shear modulus of the semimembranosus immediately or at 1 to 48 h after combined eccentric knee flexions (30 maximal voluntary eccentric contractions of knee flexion and 18 repetitions of Nordic hamstring exercise with body weight load). Moreover, Kawama et al.[11] reported that the shear modulus of the biceps femoris long head or semitendinosus did not change at 3 to 60 min after eccentric-only stiff-leg deadlift with a load of 60 % of the body mass at 0% to 50% of the maximal exercise ROM or 50% to 100% of that. They also observed insignificant changes in the shear modulus of the semimembranosus at 3 to 60 min after eccentric-only stiff-leg deadlift at 0% to 50% of the maximal exercise ROM. Similar results were observed by Kawama et al.,[12] who demonstrated insignificant changes in the shear modulus of the biceps femoris long head at 3 to 60 min after eccentric-only stiff-leg deadlift at both short and long muscle lengths with a short duration or that at long muscle lengths with a long duration. Additionally, they reported insignificant changes in the shear modulus of the semimembranosus at 3 to 60 min after eccentric-only resistance exercise at short and long muscle lengths with a short duration. Meanwhile, these studies simultaneously reported acute increases[7–9] or decreases[10–13] in passive stiffness of the other measured muscles at the same time points. These findings suggest that the acute effects of eccentric exercises on passive muscle stiffness differ among measured muscles.

****Table. 1 near here****

Methodological considerations and implications

Acute changes in passive muscle stiffness induced by resistance exercise could be influenced by several methodological factors (e.g., measured muscles, joint positions [muscle lengths], and time points). The first methodological factor is muscles used for passive stiffness measurements. As reviewed in the previous sections, some studies have observed that the acute changes in shear modulus induced by resistance exercises were inhomogeneous among the individual muscles within the knee extensors[7,9)] and knee flexors[11,12,22,23)] at the same time point. Hence, passive stiffness should be measured in several muscles to comprehensively understand the resistance exercise-induced acute changes in the stiffness. The second methodological factor is joint positions at which passive muscle stiffness was measured. Most previous studies measured shear modulus (or shear wave velocity) at relatively long muscle lengths,[9–13,19–23)] whereas only a few studies measured the shear modulus at short, medium, and long muscle lengths.[7,8,14)] The latter three studies reported the acute changes in the shear moduli at relatively long muscle lengths, but not at short muscle lengths, after resistance exercise.[7,8,14)] These results imply that the acute changes in passive muscle stiffness are dependent on measured joint position, and measuring at the relatively long muscle lengths may be a better way to elucidate the acute effects of resistance exercise on passive muscle stiffness. The third methodological factor is time point for measuring passive muscle stiffness. The passive muscle stiffness was previously measured over a wide range of time scales (immediately to 72 h after resistance exercises), and many studies observed the time-course changes in the stiffness.[7–9,11,12,20,22)] Some studies reported that muscle shear modulus decreased immediately and then returned to the baseline at 60 min after eccentric resistance exercise with a relatively low load and volume.[11,12] Other studies showed that the shear modulus considerably increased at 24 h, and its increase lasted up to 48 to 72 h after eccentric exercise with relatively high load and volume.[8,9] These findings suggest that the acute changes in passive muscle stiffness depend on measured time point, and the passive stiffness should ideally be measured over a wide range of time scales, especially after a high load and/or volume eccentric exercise.

Future direction

As reviewed in the previous sections, many studies have investigated acute changes in passive muscle stiffness after resistance exercise. To the best of our knowledge, only five studies have investigated chronic changes in passive muscle stiffness after resistance training (> 6 weeks). Among them, four studies reported insignificant changes,[29–32] and one study reported an increase[33] in passive muscle stiffness after training intervention. These studies adopted resistance exercises with eccentric contractions, a moderate to high volume (approximately 20 to 70 repetitions) per session, and a short duration (1 to 2 s) per repetition. Based on the suggestions of the present review, such types of resistance exercises could induce insignificant changes or increases in passive muscle stiffness. Meanwhile, our previous studies suggest that eccentric-only resistance exercise with a wide ROM[11] and the eccentric-only exercise with a combination of long muscle lengths and a long duration[12] immediately decrease passive muscle stiffness when performed with a low to moderate load and/or volume. Acute changes in passive muscle stiffness were suggested to be associated with its chronic changes in previous studies using static stretching.[34,35] Based on this suggestion, training intervention with protocols in the studies[11,12] may chronically decrease passive muscle stiffness. However, to the best of our knowledge, few studies directly investigated the relationships between resistance exercise-induced acute changes in passive muscle stiffness and its chronic changes after long-term resistance training. Future studies are warranted to reveal whether intervention using resistance exercises that acutely decrease passive muscle stiffness can chronically decrease the stiffness.

To date, less is known about the underlying mechanism(s) of exercise-induced acute changes in passive muscle stiffness. Previous studies have suggested some possible factors (e.g., the number of stable cross-bridges, titin, and intramuscular connective tissues) that influence the passive muscle stiffness.[36–39] First, the passive muscle stiffness was stated to be influenced by the stable binding (cross-bridges) of myosin to actin filaments, known as the main protein filaments of a sarcomere.[36] Hill[36] discussed that some cross-bridges exist stably in the relaxed state and generate a passive tension to stretching of a sarcomere. Second, the passive muscle stiffness is also influenced by titin, a giant elastic protein that spans half of the sarcomere from the Z-disc to the M-line regions. The titin acts as a spring to maintain the central position of the myosin filament within the sarcomere and develops the passive tension to stretching of the sarcomere.[37] Third, the passive muscle stiffness is affected by the intramuscular connective tissues, such as the endomysium and perimysium. The intramuscular connective tissues contain abundant collagen with fibrous networks.[38] During the early phase of muscle elongation, the collagen fibers are straightened and then elongated with the development of a passive tension during the late phase of muscle elongation.[39] Hence, the intramuscular connective tissues would generate the passive tension when the muscle is highly elongated. To the best of our knowledge, less information is available about whether resistance exercises with different program variables change the mechanical and/or structural properties of the three possible factors and how such changes, if any, are associated with the acute changes in passive muscle stiffness. Clarifying this point would be fundamental information to develop effective resistance exercise programs that can acutely change passive muscle stiffness purposefully.

Conclusion

The present review provided an overview of the types of resistance exercises that induce acute changes or insignificant changes in passive muscle stiffness that: 1) muscle stiffness is acutely increased by eccentric-only resistance exercise with a combination of a wide ROM, a high load and a high volume; 2) muscle stiffness is acutely decreased by eccentric-only resistance exercise with a combination of a wide ROM, long muscle lengths, and a long duration when the exercise is performed with a low to moderate load and/or volume; 3) passive muscle stiffness does not acutely change after concentric-only resistance exercise; and 4) acute changes in passive stiffness after resistance exercise depend on measured muscles, joint positions, and time points. These suggestions may provide helpful information for practitioners to help minimize the risk of musculoskeletal injuries and maintain physical performance.

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Conflict of interests

All authors declare no conflict of interests.

Author contributions

RK and TW conceived this narrative review article. RK collected previous published articles and wrote the original draft. TH, and TW reviewed and edited the original draft. All authors read and approved the present manuscript.

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Table 1. Overview of previous studies investigating acute changes in passive muscle stiffness after resistance exercise

Author/Year	Exercise	Contraction mode	Load	Exercise ROM	Duration per repetition (s)	Repetition	Set	Muscle	Measurement position	Measurement time point	Results
Lacourpaille et al. 2014	**EF**	**ECC**	**MVC**	**5° EF to 120° EF**	**About 1**	**10**	**3**	**BB (proximal)**	**20° EF, 90° SABD**	**Pre, 1 h, 48 h, 3 week after**	**Increase (1h: 81±70%, 48h: 39±25% [all regions], 3 week: 14±19% [all regions])**
								BB (middle)			**Increase (1h: 78±55%)**
								BB (distal)			**Increase (1h: 78±69%)**
								BA (middle)			**Increase (1h: 55±44%)**

								BB (proximal)	**70° EF, 90° SABD**		**Increase (1h: 42±28%)**
								BB (middle)			**Increase (1h: 54±33%)**
								BB (distal)			**Increase (1h: 48±30%)**
								BA (middle)			**Increase (1h: 43±36%)**
								BB (proximal)	**110° EF, 90° SABD**		**Not change**
								BB (middle)			**Not change**
								BB (distal)			**Not change**
								BA (middle)			**Not change**
Agten et al. 2016	**EF**	**ECC**	**90% RM**	**Full EF to full EE**	**3-5**	**12**	**3**	**BA**	**Slightly elbow flexed position**	**Pre, 15 min, 12 h, 24 h, 48**	**Increase in male participants**

			during CON						(not controlled)	h, 72 h, 1 week after	Increase in female participants
Guilhem et al. 2016	PF	ECC	MVC	Full PF to full DF	About 1.3	30	10	MG	0° DF, approximately 0° KF	Pre, immediately, 48 h after	Increase (IMD: 28±49%)
Pournot et al. 2016	EF	Concentric, Eccentric	70% RM during CON	Full EF to full EE	1-2 (CON), 5 (ECC)	10	4	BB	0° EF	Pre, immediately, 5 min after	Increase (IMD: 53±48%, 5 min: 31±46)
Lacourpaille et al. 2017	KE	ECC	MVC	10° KF to 110° KF	About 1.6	15	5	Knee extensors (pooled value of RF, VL, and VM)	110° KF, 85° HF	Pre, 30 min after	Increase (30 min: 27±19%, Cohen's d = 0.89)
						30	5				Increase (30 min: 79±67%, Cohen's d = 1.28)
						15	5				Not change

				30	5		90° KF, 85° HF	Increase (30 min: 65±56%, Cohen's *d* = 1.22)
				15	5		30° KF, 85° HF	Not change
				30	5			Not change
EF	ECC	5° EF to 120° EF	About 1	10	3	Elbow flexors (pooled values of BB and BA)	20° EF, 90° SABD	Increase (30 min: 71±44%, Cohen's *d* =1.91)
				10	6			Increase (30 min: 154±192%, Cohen's *d* = 1.18)
				10	3		70° EF, 90° SABD	Not change
				10	6			Not change
				10	3		110° EF, 90° SABD	Not change
				10	6			Not change

									20° EF, 90° SABD		Not change
		CON				10	3		70° EF, 90° SABD		Not change
									110° EF, 90° SABD		Not change
								RF	90° KF, approximately 0° HF		Increase (IMD: 37±57, 48h: 22±36%)
								VL			Decrease (IMD: <−10)
								VMO			Not change
Xu et al. 2018	KE	ECC	MVC	30° KF to 110° KF	About 6	75	1	RF	60° KF, approximately 0° HF	Pre, immediately, 48 h after	Not change
								VL			Decrease (IMD: <−10)
								VM			Not change
								RF	30° KF, approximately 0° HF		Not change
								VL			Not change
								VMO			Not change

Chalchat et al. 2020	KE	ISO	MVC	90° KF	5	10	6	VL	90° KF, 90° HF	Pre, immediately, 20 min after	Decrease (IMD: −58±5%, 20 min: −27±10%)
Kisilewicz et al. 2020	SE	ECC	MVC	Lowest position to highest position of shoulder joint	Not described	10	5	UTRAP (four regions)	Not described	Pre, 24 h after	Decrease
Ema et al. 2021	KE (at supine position)	ECC	MVC	40° KF to 110° KF	About 1	10	10	RF (proximal)	40° HF, 90° KF	Pre, 24 h, 48 h, 72 h after	Increase
								RF (distal)			Increase
								VL			Not change
								VM			Not change
	KE (at seated position)							RF (proximal)			Increase
								RF (distal)			Increase
								VL			Not change

								VM			**Not change**
Goreau et al. 2022	**KF**	**ECC**	**MVC**	**10° KF to 90° KF**	**About 2.6**	**15**	**5**	**BFlh** **ST** **SM**	**30° KF, 70° HF**	**Pre, 30 min after**	**Increase** **Increase** **Not change**
Zhi et al. 2022	**KF**	**CON** **ECC**	**MVC**	**0° KF to 90° KF**	**4.5**	**5**	**1**	**BFlh**	**Approximately 0° KF, 70° HF**	**Pre, 30 s, 60 s, 90 s, 120 s after**	**Not change** **Decrease (30 s: Cohen's *d* = 0.95, 60 s: Cohen's *d* = 1.30, 90 s: Cohen's *d* = 1.39, 120 s: Cohen's *d* = 1.44)**
Voglar et al. 2022	**KF, NH**	**ECC**	**MVC (KF), Body weight (NH)**	**Not described (KF), About 90° KF to full KE (NH),**	**Not described**	**10 (KF), 6 (NH)**	**3 (both exercises)**	**BFlh** **ST**	**30° KF, 60° HF**	**Pre, immediately, 1 h, 24 h, 48 h after**	**Increase (IMD: 22±34%)** **Increase (IMD: 15±5%, 1h: 16±7%,**

											24h: 17±8%)
								SM			Not change
Kawama et al. 2022	SDL	ECC	60% of body weight	0 to 100% of maximal exercise ROM	2	10	3	BFlh	80% of maximal ROM for the individual participants	Pre, 3 min, 30 min, 60 min after	Not change
								ST			Not change
								SM			Decrease (3 min: −4% [−10 to −1%], *r* = 0.45)
				0 to 50% of maximal exercise ROM				BFlh			Not change
								ST			Not change
								SM			Not change
		CON		0 to 100% of maximal exercise ROM				BFlh			Not change
								ST			Not change
								SM			Not change
Kawama et al. 2023	SDL	ECC	60% of body weight	0 to 50% of maximal exercise of ROM	2	10	3	BFlh	80% of maximal ROM for the	Pre, 3 min, 30 min, 60 min after	Not change
								ST			Not change
								SM			Not change

		50 to 100% of maximal exercise of ROM	2		BFlh	individual participants	Not change
					ST		Not change
					SM		Not change
		50 to 100% of maximal exercise of ROM	5		BFlh		Not change
					ST		Decrease (30 min: −8% [−12 to −5%], *r* = 0.72)
					SM		Decrease (3 min: −9% [−10 to 3%], *r* = 0.56, 60 min: 3% [−1 to 5%], *r* = 0.66)

%Changes in passive muscle stiffness between pre- and post-resistance exercise (corresponding time points) are presented as mean value ± standard deviation or median value (interquartile range) with effect sizes (Cohen's *d* or *r*). BA, brachialis; BB, biceps brachii; BFlh, biceps femoris long head; CON, concentric contraction; DF, dorsiflexion; ECC, eccentric contraction; EE, elbow extension; EF, elbow flexion; HF, hip flexion; ISO, isometric contraction; KF, knee flexion; MG, gastrocnemius medialis; MVC, maximal voluntary contraction; NH, Nordic hamstring; plantarflexion; RF, rectus femoris; RM, repetition maximum; ROM, range of motion; SABD, shoulder abduction; SDL, stiff-leg deadlift; SE, shoulder elevation; SM, semimembranosus; ST, semitendinosus; UTRAP, upper trapezius; VL, vastus lateralis; VM, vastus medialis; VMO, vastus medialis oblique; IMD: immediately after.