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Effects of immediate vs. delayed massage-like loading on skeletal muscle viscoelastic properties following eccentric exercise

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ABSTRACT

Background: This study compared immediate versus delayed massage-like compressive loading on skeletal muscle viscoelastic properties following eccentric exercise.
Methods: Eighteen rabbits were surgically instrumented with peroneal nerve cuffs for stimulation of the tibialis anterior muscle. Rabbits were randomly assigned to a massage loading protocol applied immediately post exercise ($n = 6$), commencing 48 h post exercise ($n = 6$), or exercised no-massage control ($n = 6$). Viscoelastic properties were evaluated in vivo by performing a stress-relaxation test pre- and post-exercise and daily pre- and post-massage for four consecutive days of massage loading. A quasi-linear viscoelastic approach modeled the instantaneous elastic response (AG_0), fast (g_1^p) and slow (g_2^p) relaxation coefficients, and the corresponding relaxation time constants τ_1 and τ_2.
Findings: Exercise increased AG_0 in all groups ($P < 0.05$). After adjusting for the three multiple comparisons, recovery of AG_0 was not significant in the immediate ($P = 0.021$) or delayed ($P = 0.048$) group compared to the control group following four days of massage. However, within-day (pre- to post-massage) analysis revealed a decrease in AG_0 in both massage groups. Following exercise, g_1^p increased and g_2^p and τ_1 decreased for all groups ($P < 0.05$). Exercise had no effect on τ_2 ($P > 0.05$). After four days of massage, there was no significant recovery of the relaxation parameters for either massage loading group compared to the control group.
Interpretation: Our findings suggest that massage loading following eccentric exercise has a greater effect on reducing muscle stiffness, estimated by AG_0, within-day rather than affecting recovery over multiple days. Massage loading also has little effect on the relaxation response.

1. Introduction

Unaccustomed eccentric exercise (EEX) results in delayed onset muscle soreness, presenting clinically as pain, stiffness, and decreased range of motion. These symptoms are attributed to tissue inflammation and the disruption of the cellular components, thus altering the muscle's structure and subsequently the tissue's viscoelastic response (Lieber and Friden, 2002; McHugh et al., 1999; Page, 1995). Various approaches to characterize the viscoelastic properties of both human and animal skeletal muscle in response to EEX have been utilized (Chleboun et al., 1998; Howell et al., 1993; Jones et al., 1987; Pousson et al., 1990; Whitehead et al., 2001). Changes in muscle mechanical properties (particularly increased stiffness), increased tissue swelling, and decreased joint range of motion have been observed 4–6 days following unaccustomed EEX (Chleboun et al., 1998; Jones et al., 1987). Additional studies have estimated changes in human skeletal muscle stiffness by measuring joint torque–angle properties (Chleboun et al., 1993, 1998; Whitehead et al., 2001). Moreover, Howell et al. (1993) noted that passive elbow stiffness doubled immediately following EEX and remained elevated for 4 days. The increase in stiffness was estimated from the slope of the first 50° of the torque–angle curves of the elbow flexors and is therefore not a measure of the tissue's passive stiffness. In a recent study, Green et al. (2012) employed magnetic resonance elastography to directly measure changes in the in vivo elastic properties of the human triceps surae after EEX. The investigators noted that both the storage modulus (elastic component) and the shear loss modulus (viscous component) increased after exercise in the gastrocnemius and remained elevated for one week.

Massage therapies have been shown to reduce muscle soreness following unaccustomed exercise (Farr et al., 2002; Hilbert et al.,

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2003; Smith et al., 1994; Zainuddin et al., 2005). Several animal models and theoretical approaches have been developed to understand the effects of compressive loading on muscle mechanical properties. As a result, these pursuits have sought to provide possible mechanisms to explain the effects of these manual therapies on tissue function. Bosboom et al. (2001) performed a ramp and hold compression test on rat skeletal muscle and utilized an Ogden model to estimate both elastic and viscous material parameters that accurately described the muscle's behavior under compressive loading. Van Loocke et al. (2008) employed a quasi-linear viscoelastic (QLV) model to investigate the time-dependent behavior of porcine skeletal muscle and found that the muscle's viscoelastic behavior was dependent on both compression rate and fiber orientation. Haas et al. (2013) demonstrated in a rabbit model that recovery of isometric torque production following intense EEX was dependent on both magnitude and frequency of compressive loading intended to mimic clinical massage. In our lab's previous work, Haas et al. (2012b) quantified the effects of massage-like compressive loading (MLL) on the recovery of muscle viscoelastic properties and noted that tissue stiffness, rather than relaxation, was more affected. Finally, our lab's previous work has also noted that immediate and 48 hour delayed MLL had different effects on the recovery of both torque production and inflammatory cell infiltration following EEX (Haas et al., 2012a).

The purpose of the current study was to extend our previous work and to compare immediate and delayed MLL following a damaging bout of EEX and their changes in the viscoelastic properties of the muscle–tendon complex. We hypothesized that MLL applied immediately following exercise would have a greater recovery on the tissue's viscoelastic properties compared to the same regimen started 48 h post-exercise. Such information could guide clinicians in prescribing the optimal time for massage therapies following exercise in order to mitigate symptoms, such as prolonged muscle stiffness, of intense EEX.

2. Methods

All experiments were approved by the Institutional Animal Care and Use Committee (IACUC) at The Ohio State University. The rabbits were anesthetized using 5% isoflurane and maintained under anesthesia during all surgeries and experiments.

2.1. Surgical procedure and exercise protocol

Eighteen skeletally mature New Zealand White female rabbits were surgically instrumented with bilateral deep fibular (peroneal) nerve cuffs (Koh and Leonard, 1996) for consistent and reproducible stimulation of the tibialis anterior (TA) muscle. The surgical procedure is detailed in Butterfield et al. (2008). The interfaces for the nerve cuffs were subdermal on the back of each rabbit so as not to interfere with normal ambulation and activity.

The rabbits were subjected to the exercise protocol seven days after surgery. As detailed in previous works (Butterfield et al., 2008; Haas et al., 2012a,b, 2013), the rabbits were placed supine in a sling with one foot placed on a footplate attached to a Servo motor with a torque sensor (Fig. 1). The EEX protocol consisted of seven sets of ten lengthening contractions, during which the TA was stimulated at a voltage three times the α-motoneuron threshold. Two minutes of rest preceded each set of contractions in order to minimize the effects of fatigue. The parameters of the lengthening contractions are detailed in Haas et al. (2012b).

2.2. MLL protocol

The rabbits were randomized into one of three groups: immediate MLL ($n = 6$), 48 hour delayed MLL ($n = 6$), or exercised no-MLL control ($n = 6$). Each of the 18 rabbits had one hind limb exercised. MLL was applied immediately after exercise (day 1) in the immediate MLL group and 48 h after exercise (day 3) in the delayed MLL group daily (approximately 24 h apart) for four consecutive days. MLL was not applied for the control group in order to assess the effects of natural healing four days after EEX.

The rabbits were subjected to in vivo MLL using a customized device (Haas et al., 2012b; Wang et al., in press). A mechanical tip was mounted on the end of the motorized device and connected to a force sensor (Fig. 2). The tip compressed the tissue surface until a compressive

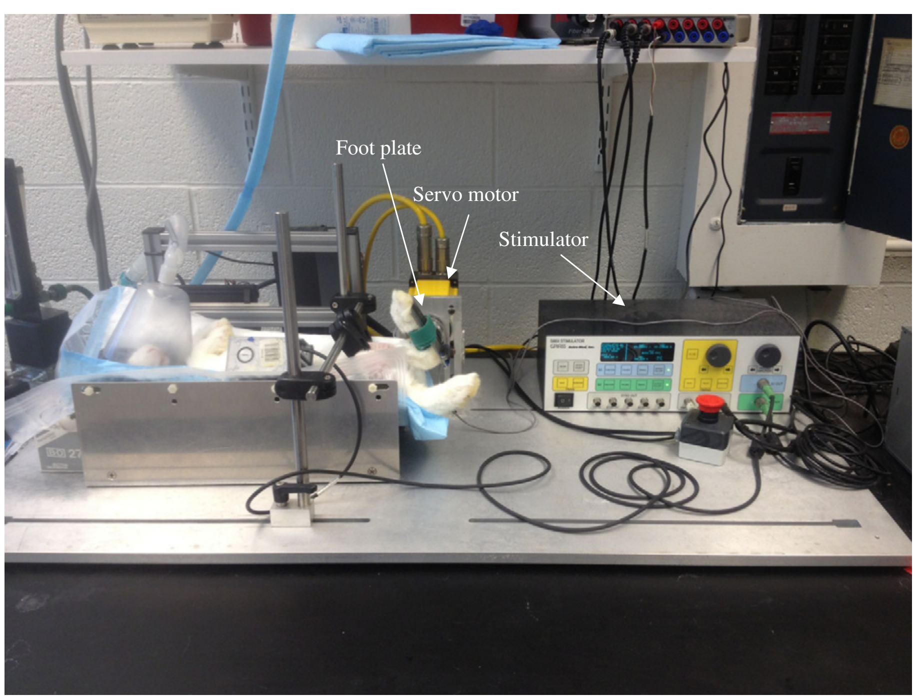

Fig. 1. Exercise protocol setup. Animal was under anesthesia and placed supine in sling. The stimulator box controlled the pulse for stimulation of the tibialis anterior. The animal underwent 7 sets of 10 eccentric contractions with an external stimulation of three times the α-motoneuron threshold.