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Impact-induced soft-tissue vibrations associate with muscle activation in human landing movements: An accelerometry and EMG evaluation

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Abstract.
BACKGROUND: Previous studies have not used neurophysiological methodology to explore the damping effects on induced soft-tissue vibrations and muscle responses.
OBJECTIVE: This study aimed to investigate the changes in activation of the musculoskeletal system in response to soft-tissue vibrations with different applied compression conditions in a drop-jump landing task.
METHODS: Twelve trained male participants were instructed to perform drop-jump landings in compression shorts (CS) and regular shorts without compression (control condition, CC). Soft-tissue vibrations and EMG amplitudes of the leg within 50 ms before and after touchdown were collected synchronously.
RESULTS: Peak acceleration of the thigh muscles was significantly lower in CS than in CC during landings from 45 or 60 cm and 30 cm heights ($p < 0.05$), respectively. However, the damping coefficient was higher in CS than in CC at the thigh muscles during landings from 60 cm height ($p < 0.05$). Significant decrease in EMG amplitude of the rectus femoris and biceps femoris muscles was also observed in CS ($p < 0.05$).
CONCLUSION: Externally induced soft-tissue vibration damping was associated with a decrease in muscular activity of the rectus femoris and biceps femoris muscles during drop-jump landings from different heights.

Keywords: Soft tissue vibrations, externally damping, muscle activity, landing

1. Introduction

Numerous studies have shown that most physical activities, including running and jump/landing, involve impacts during ground contact. Repetitive impact forces in running demonstrate a maximum of 1.5 times to 3 times body weight (BW). During two-footed landings from a vertical jump, the peak magnitudes of impact forces range from 3.5 times to 6 times BW [1,2]. These impact forces cause large transient shocks that act upon the lower body and excite local vibrations that are either absorbed or

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transmitted through the soft tissues. Such vibration characteristics (i.e., amplitude and frequency) are tissue dependent [3,4], and the related muscles react by contracting when the soft tissues are exposed to vibrations [5,6].

Theoretically, the impact force is an input signal into the human locomotor system, whereas the soft tissues are the oscillating masses [5]. When the frequency of the impact force and the natural frequency of a specific soft-tissue compartment are similar, the soft tissue will vibrate with maximal amplitude. This common frequency is the resonance frequency specific to each soft-tissue compartment. To avoid large soft-tissue vibrations that can cause micro-damage to the tissue, muscles in the lower extremity will be activated. These changes in muscle activation may result in an altered frequency of the impact force and an altered natural frequency of the soft-tissue compartment, presumably causing these frequencies to diverge and minimizing the amplitude of soft-tissue vibrations [7].

However, extra muscle activation used for damping of soft-tissue vibrations may consume additional energy during a motor task. This extra energy is calculated as about few percentages of the total energy used to complete the motor task [8,9]. The energy applied by the muscles when exposed to externally induced vibrations has been measured in highly controlled situations [10,11]. However, little is known about the muscle activity and energy required to damp vibrations during a less controlled task, such as drop-jump landing.

Generally, the muscle action required for damping soft-tissue vibrations during a drop landing and jump task cannot be well distinguished from those needed for vertical ascension. Alternatively, muscle activity may be assessed as a function of soft-tissue vibrations in a setting where the characteristics of such vibrations are modified extrinsically. Specifically, soft-tissue vibrations should be partly dampened while maintaining all other conditions (contact velocity, contact surface, etc.) constant. Compression apparel can dampen soft-tissue vibrations during various sports-related tasks and thus can be used to meet this requirement during drop-jump landing. One highly relevant study by Doan et al. [12] found significantly reduced longitudinal (0.32 cm) and anterior-posterior (0.40 cm) muscle oscillation upon landing from a maximal vertical jump. The proposed mechanism indicates that a decrease in the oscillatory displacement of the muscle may optimize neurotransmission and mechanics at the molecular level.

Previous studies have also shown that compression elevates the intramuscular pressure, alternately adding to the increase in pressure produced by the muscle contraction itself [13,14]. However, during movement, the actual pressure applied on the body exhibits periodic fluctuations. Therefore, one cannot easily determine the real-time intramuscular pressure exerted by the compression device itself in dynamic actions. No neurophysiological methodology (e.g., surface electromyography) has been involved in previous research, which further hinders our understanding of the potential mechanisms underlying the compression effects and the relationship between muscular activity and soft-tissue vibrations.

Therefore, this study aimed to investigate the changes in activation of the musculoskeletal system in response to soft-tissue vibrations with externally applied compression in increasing intramuscular pressure during a drop-jump landing. We hypothesized that enhanced extrinsic vibration damping of soft-tissue compartments is associated with reduced activity of corresponding muscles.

2. Methods

2.1. Participants

Twelve trained male volunteers (age: 23.7 years $\pm$ 2.7 years, height: 178.3 cm $\pm$ 2.5 cm, mass: 70.1 kg $\pm$ 4.6 kg), who were used to regular high-intensity training, participated in this study after providing informed written consent in accordance with the guidelines of the Ethics Committee of the Shanghai University of Sport. The inclusion criteria for the participants were: 1) free of any injuries at the time of the experiment and 2) suffered no injuries within six months prior to the experiment. Potential participants with history of significant foot or lower-limb problems and/or systemic or neurological disorders were excluded from the study.

2.2. Type of research

The current research is an experimental study with randomized repeated-measures design. It is a longitudinal study in which the subjects received a random sequence of different treatments or conditions. We adopted two shorts conditions that differed in compression attributes. One was a customized compression shorts condition. The other was a control shorts condition without compression on the thigh. The order of the shorts conditions was randomized.

2.3. Equipment and devices

2.3.1. Accelerometer

Vibrations of the quadriceps femoris and hamstring muscles through the accelerometers attached to the rectus femoris (RF) and biceps femoris (BF) were simultaneously collected using two biaxial accelerometers (Biovision Corp., Wehrheim, Germany). The measurement range of the accelerometer was $\pm$ 20 g (g = 9.81 m/s^2). The accelerometers were placed onto the skin (or compression shorts) using glue and secured with adhesive tape [15].

2.3.2. Surface electromyography

Biovision system (Biovision Corp., Wehrheim, Germany) was used to record the surface EMG signals from the RF and BF in the dominant leg. The dominant limb was defined as the preferred leg that the participant used to kick a ball [16]. Bipolar surface electrodes were placed along the longitudinal axes of the RF at approximately 50% of the distance between the anterior superior iliac spine and the superior border of the patella [17]. The BF electrodes were placed 2.5 cm medial to the midpoint of a line from the ischial tuberosity to the mid-popliteal crease [18]. The EMG system used a double differential amplifier (input impedance = 10^{12} Ω, CMRR = 120 dB at 60 Hz). EMG signals, as well as acceleration signals, were stored simultaneously at a sampling rate of 1200 Hz with the data acquisition system and DASYLab software (8.0, DATALOG GmbH, Mönchengladbach, Germany).

2.4. Experimental protocol

2.4.1. Compression shorts

The customized compression shorts (CS) used in this study was composed of 75% nylon and 25% elastane. The CS covered the area from the waist to the knee. By contrast, the control garment conditions (CC, no compression on the thigh) consisted of regular running shorts without tight-fitting underwear.

2.4.2. Drop-jump landing task

Drop-jump landing tasks included landing from a drop jump (DJ) at heights of 30 (DJ30), 45 (DJ45), and 60 (DJ60) cm. Specifically, participants were instructed to slowly slide off the platform and land with a maximum effort of upward jump as soon as possible. The order of the garment conditions, as well as the landing heights, was randomized. Three successful trials at each landing height were selected for analysis. A rest period of 2 minutes was provided between trials. For each participant, all trials were completed within 2 hours. Figure 1 illustrates the experimental procedures.

2.5. Data analysis

2.5.1. Soft-tissue vibrations

The main variables used in this study characterized the vibration signals, including peak soft-tissue acceleration (a_{peak}) and damping coefficient (c), following landing impact for each condition [19,20]. The latter parameter was determined by least-squares minimization method (Levenberg-Marquardt) of the following equation:

$$s = ae^{-ct}\sin(2\pi f_v t + \varphi)$$

where s is the measured signal, a is the amplitude of the vibration, c is the damping coefficient, f is the dominant frequency (damped), and φ is a phase coefficient. This damped oscillation model fitted to the data implicates a simple linear system. In this system, the damping characteristics in the soft tissues will result from the interaction between the ground and the tissues of the lower extremity during initial contact.

2.5.2. Muscular activity

EMG data were analyzed with DASYLab software (8.0, DATALOG GmbH, Mönchengladbach, Germany). Raw signals were band-pass filtered at 10 Hz to 400 Hz and then full-wave rectified. EMG amplitudes were normalized as a percentage of the highest value recorded during 18 trials of drop jumps [21]. Root mean square of the muscle activity (EMG_{RMS}) was calculated during pre- and post-activation phases of landing by using the following equation:

$$EMG_{RMS} = \sqrt{\frac{1}{T}\int_{t}^{t+T} EMG^2(t)dt}$$

where t is the onset of signal, and T is the time interval of each phase. Specifically, the phases were defined as follows: pre-activation phase is 50 ms before ground contact (-50 ms); and post-activation phase is 50 ms after touchdown ($+50$ ms).

2.6. Statistical analysis

All data are expressed as mean $\pm$ *SD*. Two-way ANOVAs were used to determine the compression effects and the drop heights on soft-tissue acceleration, damping coefficient, and muscle activity. Tukey's post-hoc tests were used to determine individual significant differences (17.0, SPSS Inc., Chicago, IL, U.S.A.). Significance level was set at $\alpha = 0.05$.

3. Results

A significant decrease in a_{peak} was observed in CS condition (Table 1). Specifically, for the quadriceps femoris, the a_{peak} in CS was significantly lower than that of CC during landings from 45 and 60 cm drop heights ($p < 0.05$). Similarly, for the hamstring muscles, wearing compression shorts showed a significantly lower a_{peak} than that of CC in 30 cm drop landings ($p < 0.05$); trend toward decreased a_{peak} in CS was also shown in landings at 60 cm height ($p < 0.01$).

Table 1
Comparison of peak soft tissue acceleration (a_{peak}) of quadriceps and hamstrings between compression shorts (CS) and control condition (CC) groups during landings at three different heights

Muscle groups	Shorts conditions	Landing heights		
		30 cm	45 cm	60 cm
Quadriceps femoris	CS	6.85 ± 3.1	10.25 ± 4.9	11.18 ± 4.1
	CC	7.82 ± 3.2	13.16 ± 4.4	14.31 ± 4.2
	Diff.%	−12.5%	−23.1%	−22.0%
	p-value	0.272	0.038*	0.039*
Hamstrings	CS	3.18 ± 1.2	4.07 ± 1.5	5.01 ± 1.1
	CC	4.42 ± 1.9	4.85 ± 1.0	5.92 ± 2.4
	Diff.%	−28.2%	−15.8%	−16.5%
	p-value	0.027*	0.144	0.093†

Diff.% shows percentage difference between CS and CC divided by the data of CC. * Significantly different between shorts in the same landing height with $p < 0.05$. † Significantly different between shorts in the same landing height with $p < 0.1$.

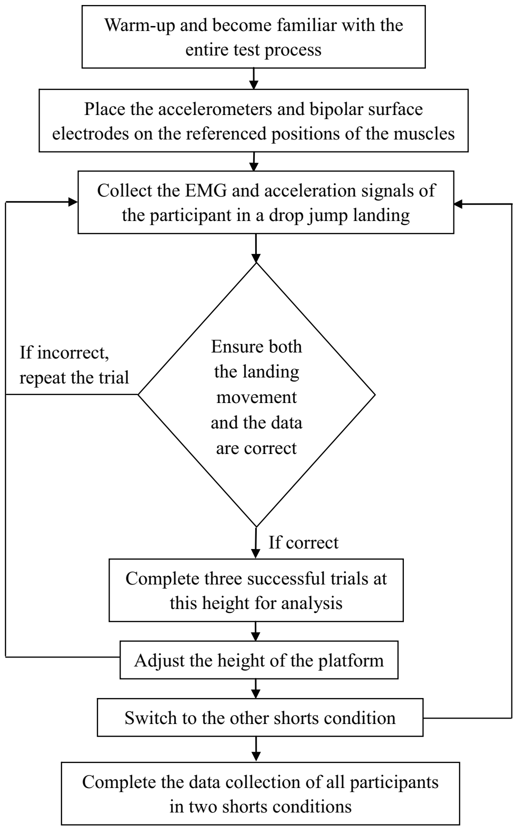

Fig. 1. Flow diagram of experimental procedures.

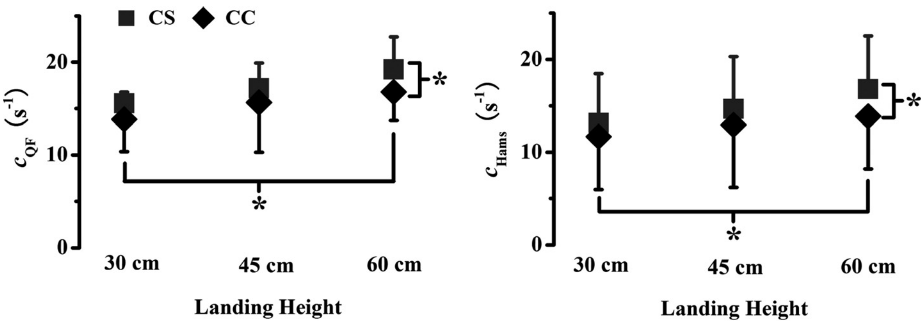

Fig. 2. Influence of compression shorts (CS) on damping coefficient (c) of quadriceps (QF) and hamstrings (Hams) vibrations during landings at three different heights.

Wearing CS can increase the c of soft-tissue vibrations during landings from different drop heights (Fig. 2). Specifically, the c of both the quadriceps femoris and hamstring muscles in CS was significantly higher than that in CC during landings at 60 cm height ($p < 0.05$). The c of the thigh muscles also increased with landing heights increasing from 30 cm to 60 cm ($p < 0.05$).

Overall, the results showed a decrease in EMG_{RMS} when wearing CS during landing (Fig. 3). Post-hoc comparisons showed that the EMG_{RMS} of the RF with CS was significantly lower than that of the CC in

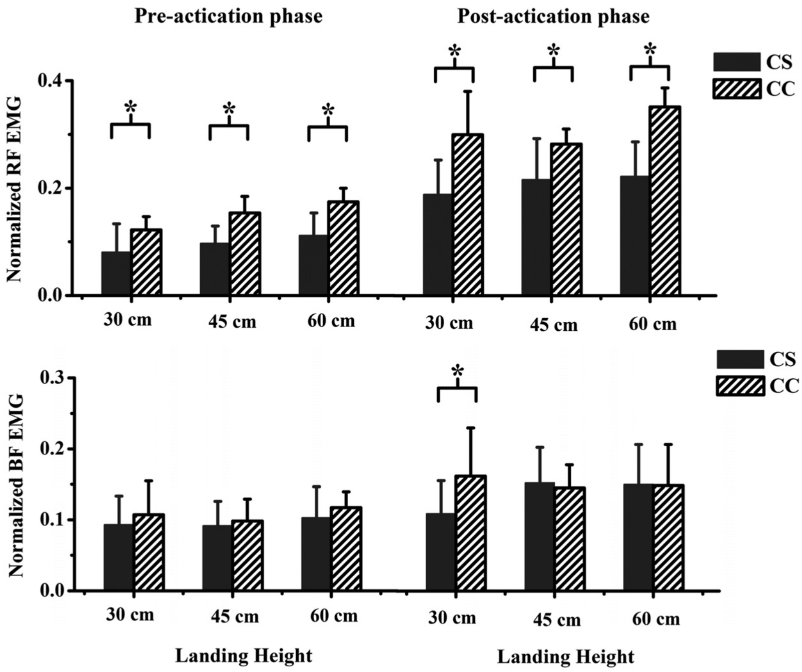

Fig. 3. Influence of compression shorts (CS) on normalized EMG of rectus femoris (RF) and biceps femoris (BF) during pre- and post-activation phases of landings at three different heights.

both pre- and post-activation phases of DJ at all heights ($p < 0.05$). For the BF, a significant decrease in EMG_{RMS} was observed in CS compared with that in CC during post-activation phase of landing at 30 cm ($p < 0.05$).

4. Discussion

In the current study, we adopted a drop-jump landing task to evaluate the relationship between muscular activity and soft-tissue vibrations. The results showed a significant decrease in muscle activity and an increase in the damping coefficient of soft-tissue vibrations during landings from different drop heights. Although a direct causal relationship between partial damping and muscle activity cannot be inferred from these results, these findings are supported by previous studies that have found similar relations between muscle activity and soft-tissue vibration damping in highly controlled experiments. For instance, muscle activities of greater vasti, gastrocnemii, and biceps femoris increased the damping of corresponding soft tissue (quadriceps, triceps surae, and hamstrings) vibrations during controlled isometric and isokinetic contractions [4]. Externally applied whole body vibrations at 35 Hz also induced $> 40\%$ increase in the muscle activities of vasti and gastrocnemii during squatting [6]. Hence, muscle activities and soft-tissue vibrations are closely associated.

A recent work proved that the middle trapezius muscle activity did not vary significantly following a 30 s vibration intervention [22]. Similarly, Cormie et al. [23] found that a 30 s whole body vibration intervention did not increase the muscle activities of vasti and BF while performing a counter-movement jump following the intervention. These findings indicate that relative gains in muscle activity associated with vibrations and relative reductions in muscle activity with extrinsic damping occur only during the actual vibration exposure.

In this investigation, partial damping of soft-tissue vibrations affected not only post-landing muscle activation but also pre-landing activation. These results indicate that muscle activity may be sensitive not only to directly applied vibrations, but also to changes in preparation for expected vibrations before landing. Similarly, muscle activities in lower leg muscles were increased during expected landing on a harder surface. However, during unexpected landing on a harder surface, the frequency content of the input signal shifted closer to the natural frequency of the soft-tissue compartments, and muscle activity remained unchanged as soft-tissue acceleration increased [24]. Therefore, partial vibration damping may be responsible for decrease in muscle activity before landing.

Whole-body vibrations induced an increase in post-activation potentiation of vastus lateralis twitch in a static squat position [25]. Extrapolating these results to jump landing, the observed greater pre-landing activity can be interpreted as a temporary post vibration of exposure residual activation, which can increase EMG activity in the absence of vibrations. These results oppose earlier findings from the same group, showing no increase in muscle activity after vibration exposure [22]. Nevertheless, to date, no unique mechanism can explain the relation between partial soft-tissue vibration damping and muscle activation.

To our knowledge, few studies have examined the relationship between partial damping of soft-tissue vibrations and reduction in muscle activity during jump landing. The current findings imply both the understanding of mechanisms modulating the active damping of vibrations and the energetics of soft-tissue vibrations. Although some data can explain the relation between soft-tissue vibrations and muscle activity during controlled experiments [6,26], little is known about this relation during complex activities, such as jump landing. The decrease in soft-tissue vibrations associated with decline in muscle activity during landings confirms that active damping of soft-tissue vibrations is also manifested during complex tasks involving such vibrations. Muscle activity can also be related to energy consumption, although no direct and unique relation exists [27]. Therefore, changes in muscle activity caused by or related to active damping presumably influence energy utilization positively. Consequently, the observed relation between partial soft-tissue vibration damping and muscle activity may represent a correlation between partial damping and muscle energy consumption.

Another inference of the current findings is the possibility of reducing energy consumption required to complete a given task by minimizing soft-tissue vibrations. Hence, a reduction in muscle activity related to external damping of soft-tissue vibrations can decrease the total energy consumption and accordingly increase the performance in an endurance task. However, given the complexity of factors contributing to locomotion efficiency, assessment of the influence of decreased muscle activity on locomotion economy is challenging [28]. Although a reduction in muscle activity is associated with a decrease in muscle energy consumption, this relationship is yet to be quantified in jumping/landing and running. To date, the observed relation between muscle activity and external damping as a mechanical phenomenon or rather a physiological response to compression remains uncertain. An unexpected finding is discovered when the gain in muscle contraction efficiency following exposure to vibrations is considered. After a bout of mechanical vibration treatment, the ratio between the activity of biceps brachii and the mechanical power developed by the muscle decreased significantly [29]. Based on these findings, the required mechanical power during this experiment did not change between conditions, and an absolute decrease in muscle activity is expected when the external damping is increased. However, future studies should focus on the possible relationships among soft-tissue vibration damping, muscle activity, and muscle energy consumption. The information can be further used to decrease energy consumption and possibly increase performance during physical activity involving exposure to vibrations.

In conclusion, externally induced soft-tissue vibration damping was associated with a decrease in muscular activity of the rectus femoris and the biceps femoris muscles during drop-jump landing from different heights. A greater increase in the damping is associated with a greater decrease in muscle activity. Although no causal relationship between changes in damping and changes in muscle activity can be inferred, these findings contribute to further understanding and manipulation of parameters specific to landing and other activities involving soft-tissue vibrations.

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