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# Active versus local vibration warm-up effects on knee extensors stiffness and neuromuscular performance of healthy young males

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## A B S T R A C T

**Objectives:** To compare the effects of local-vibration and active warm-up on knee extensors muscle stiffness and neuromuscular performance.

**Design:** Experimental crossover study.

**Methods:** Thirteen participants performed three 15-min warm-up protocols of control (CON), active (ACT) and local-vibration (LV) in separate testing session. Passive stiffness of vastus lateralis (VL) and vastus medialis (VM) by shear wave elastography and neuromuscular performance were assessed before and 2-min after each condition.

**Results:** A decrease in muscle stiffness was reported after ACT for VL ( $-16.0 \pm 6.6\%$ ;  $p < 0.001$ ) and VM ( $-10.2 \pm 8.7\%$ ;  $p = 0.03$ ) while no changes were reported after CON ( $p = 0.46$  and  $p = 0.34$  for VL and VM, respectively) and LV ( $p = 0.07$  and  $p = 0.46$  for VL and VM, respectively). Maximal jump performances increased during squat ( $+8.5 \pm 6.6\%$ ;  $p < 0.001$ ) and countermovement jump ( $+5.2 \pm 5.8\%$ ;  $p < 0.001$ ) after ACT while no changes were reported after CON and LV during squat ( $p = 0.16$  and  $p = 0.81$ , respectively) and countermovement jump ( $p = 0.18$  and  $p = 0.31$ , respectively). We further report that each condition was ineffective to inducing changes in maximal voluntary isometric contraction force ( $p = 0.18$ ), rate of force development ( $p = 0.92$ ), twitch parameters ( $p > 0.05$ ) as well as central modulations as reported by the unchanged voluntary activation level ( $p = 0.24$ ) and maximal electromyography (EMG) recorded from the VL ( $p = 0.44$ ).

**Conclusions:** The active warm-up acutely reduced muscle stiffness and increased muscle performance during maximal dynamic tasks. With regard to LV, further studies are required to determine optimal parameters (frequency, amplitude, duration) to significantly increase muscle performance.

## 1. Introduction

Active warm-up protocols are an accepted practice to positively influence muscle performance.<sup>1</sup> Alternatively, vibration exercise, mainly through whole-body vibration protocols, has been proposed as a potential warm-up modality.<sup>2</sup> However, several limitations associated with the use of vibrating platforms or their alternatives (e.g., prohibitive cost, non-portability of the system or inability to

directly target a specific muscle group) limit their utilization.<sup>3,4</sup> Thus, the ease and use of local vibration (LV) may provide an alternative method for warm-up;<sup>5</sup> as such, a recently manufactured LV device known as the Myovolt<sup>TM</sup><sup>3,4</sup> has been proposed to increase muscle performance. However, due to the limited research the efficiency of this device remains equivocal. Using the Myovolt<sup>TM</sup>, for 10 min with a pulsing frequency was ineffective at increasing maximal voluntary contraction (MVC), rate of force development (RFD) and muscle activation in healthy trained males.<sup>3</sup> In contrast, it was reported to increase peak and mean power in master field-hockey players, without any concomitant changes in electromyography (EMG) amplitude,<sup>4</sup> possibly through peripheral ergogenic effects. Alternatively, modulations in corticospinal function may also be involved,<sup>5,6</sup> as suggested in knee extensors by the decrease in active motor threshold<sup>6</sup> and the increase in EMG amplitude<sup>7</sup> following isometric squats with superimposed LV, despite no associated

*Abbreviations:* CMJ, counter movement jump; EMG, electromyography; LV, local vibration;  $M_{max}$ , maximal M-wave recorded on relaxed muscles; MVC, maximal voluntary contraction; PNS, peripheral nerve stimulation; RFD, rate of force development; RMS, root mean square; SJ, squat jump; VA, voluntary activation; VJ, vertical jump; VL, vastus lateralis; VM, vastus medialis.

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changes in MVC and RFD. Considering these equivocal results, future investigations are needed before LV, especially Myovolt™, may be routinely used by athletes and coaches as a warm-up modality to increase muscle performance.

If the enhanced muscle performance after various warm-up protocols has been mainly related to temperature changes,<sup>8</sup> other mechanisms may also be involved (e.g., increased blood flow to muscles, post-activation potentiation).<sup>9</sup> It has been suggested that a decreased passive muscle stiffness may also contribute to an increased RFD and power during short-duration tasks<sup>9</sup> and has been linked to injury occurrence in elite athletes, e.g., hamstring strains.<sup>10</sup>

Muscle stiffness may be investigated in vivo through elastography techniques such as supersonic shear imaging (SSI) by measuring shear modulus from shear wave propagation velocity.<sup>11</sup> An increased intra-muscular temperature is purported to decrease hamstring shear modulus after an active warm-up.<sup>12</sup> Alterations in viscoelastic and thixotropic muscle properties, such as a breaking of actin-myosin bonds, may also be involved reducing passive muscle stiffness after warm-up.<sup>9</sup> For instance, it has been reported that mechanical agitation, including vibration, reduced passive torque during passive movement,<sup>13</sup> suggesting a decreased number of residual cross-bridges spontaneously formed at rest. Nonetheless, it remains to be determined if LV devices such as the Myovolt™ can reduce muscle stiffness and how this may contribute to increased muscle performance. Therefore, the aim of the present study was to investigate the acute effect of the Myovolt™ on neuromuscular performance and passive stiffness of knee extensors in comparison to a conventional active warm-up.

## 2. Methods

Thirteen physically active (4–6 h of recreational sport activities per week) males (age:  $24 \pm 3$  years, height:  $181 \pm 6$  cm, body mass:  $75 \pm 8$  kg) participated in this study. The sample-size was calculated from an expected “medium” effect size for pre-post MVC changes, with  $\alpha$  level of 0.05, power of 0.8 and repeated measure correlation of 0.85. All participants were free of lower limb injury during the previous 3 months. Written informed consent was obtained from all participants. This study was approved by the local ethics committee.

After a familiarization session, participants were involved in three testing sessions including a specific warm-up condition randomly ordered: control (CON), active (ACT) or local vibration (LV). Each testing session was separated by one week. After a 20-min resting period on a chair, measurements were performed on the dominant leg before (PRE) and 2-min after (POST) CON, ACT or LV. The flowchart of the study design is presented in Fig. 1.

For ACT, participants performed 10-min on a cycle ergometer (Monark 839E, Monark Exercise AB, Vansbro, Sweden) at a constant power output of 100 W (cadence of 60 rpm). This was followed by 2-min of unloaded bilateral back squats at a tempo of 2-s up and 2-s down at a knee angle of approximately 120°. The last exercise, involved 2-min of an unloaded alternate leg bounding performed on a 15-m indoor track. On completing 15-m, participants walked back to the start position until 2-min was completed. One-minute rest intervals separated each exercise.

For LV, two vibratory devices (MyoVolt™, Christchurch, New Zealand) were positioned on the right and left thighs. During LV, participants were seated with hips and knees at 90° and remained relaxed. As previously used in research<sup>3,4</sup> and according to the manufacturer’s instructions, the pulse mode of the device (i.e., 0.5-s ON; 0.5-s OFF) was activated for 15 min. The vibration frequency passed through a range of 0–170 Hz at amplitude of 0–0.12 mm during

the 0.5-s, which created a pulsing effect. For the control condition, participants rested in a seated position for 15 min.

Participants were seated upright with both right knee and hips at 90° of flexion in a custom-built chair allowing isometric force measurement. EMG amplitude of the vastus lateralis (VL) were recorded with pairs of self-adhesive surface electrodes (Meditrace 100) placed at two-thirds on the line from the anterior spina iliaca superior to the lateral side of the patella. EMG signals were amplified with an octal bio-amplifier (ML138, ADInstruments, Bella Vista, Australia), bandpass filtered (5–500 Hz) and analogue-to-digital converted. Force and EMG data were acquired using a PowerLab data acquisition system (16/30-ML880/P, ADInstruments, Bella Vista, Australia) at a sampling rate of 2 kHz.

Femoral electrical nerve stimulation was used to record EMG and force evoked responses. Single rectangular electrical pulses with 1-ms duration and 400 V maximal output were delivered via constant-current stimulator (DS71, Digitimer, Hertfordshire, UK) to the right femoral nerve via a 30-mm diameter surface cathode (Meditrace 100, Covidien, Mansfield, MA) that was taped to the skin of the femoral triangle, and a 50 × 90 mm anode (Durastick Plus; DJO Global Vista, CA, USA) to the gluteal fold. To determine the optimal intensity of stimulation, single stimuli were delivered incrementally by steps of 10 mA until resting VL M-wave amplitudes plateaued. The optimal intensity was then increased by 20% to confirm supramaximality.

Then, participants were asked to perform three brief voluntary contractions (interspaced by 30-s of rest) with the instruction to contract as fast as possible to assess the rate of force development (RFD). Maximal RFD was defined as the peak of the first derivative of the force-time curve from the onset of contraction, and was normalized to body mass.

Subsequently, participants performed two 3-s MVCs with superimposed electrical stimulation to assess the voluntary activation (VA) level. Three electrical nerve impulses were delivered during the MVCs in the following order: (i) superimposed paired stimulation (i.e., doublet, frequency: 100 Hz) to the force plateau; (ii) potentiated doublet 3-s after the MVC and (iii) potentiated single stimulation 5-s after the MVC to obtain the maximal amplitude of the resting M-wave. The two MVCs were interspaced by 1 min of rest. Maximal force was considered as the highest peak force recorded before the PNS stimulation from the two MVCs. Root mean square (RMS; using a 20-ms sliding window) EMG was calculated for VL over a 500-ms period after maximal force and then normalized to  $M_{max}$  (see below). Maximal voluntary activation (VA) was estimated by using the twitch interpolation technique, following this formula:

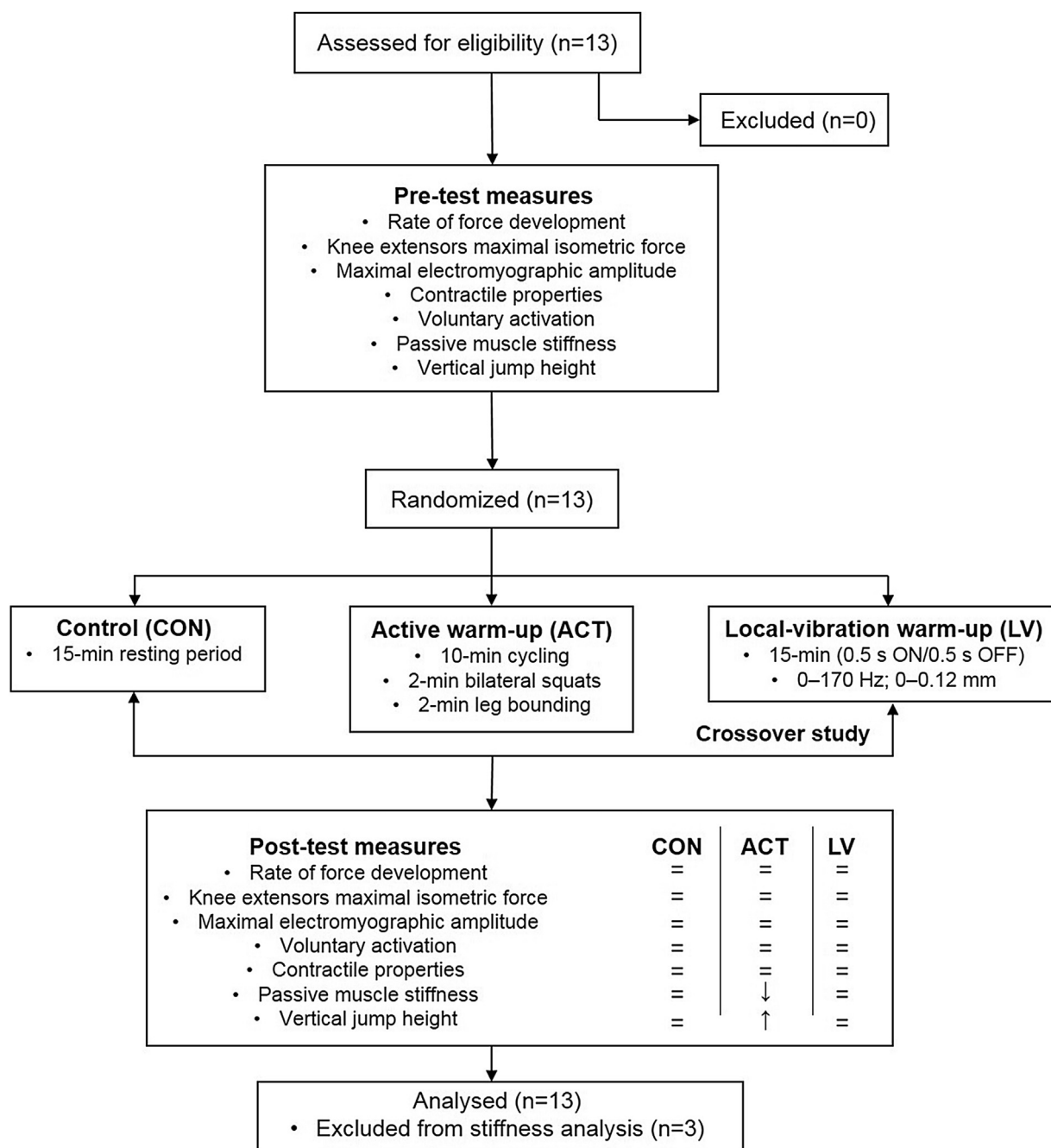
$$VA(\%) = [(1 - DB_{SUP}/DB)] * 100$$

with  $DB_{SUP}$  the force evoked by the superimposed paired stimulation to the MVC and  $DB$  the force evoked by the potentiated doublet 3-s after the MVC in a relaxed state. VL M-wave peak-to-peak amplitude ( $M_{max}$ ) was measured as the mean from the EMG responses to potentiated single stimulation.

Contractile properties of the knee extensors were assessed during resting doublets and included the following variables: DB, contraction time, half-relaxation time, and peak rate of force development.<sup>14</sup>

Passive stiffness was then assessed from vastus lateralis (VL) and vastus medialis (VM) muscles. Muscle shear modulus was measured using an AixPloer ultrasonic scanner (version 6.1.1; Supersonic Imagine, Aix-en-Provence, France) coupled with a linear transducer array (4–15 MHz, musculo-skeletal preset, SuperLinear15-4, Vermon, Tours, France). The shear elastic modulus ( $\mu$ ) was calculated as follows<sup>11</sup>:

$$\mu = \rho \cdot V_s^2$$



**Fig. 1.** Flow diagram representing study design and primary outcomes.

with  $\rho$  the muscle mass density ( $1000 \text{ kg/m}^3$ ), and  $V_s$  is the speed of shear wave induced by focused ultrasonic beams.

While participants were seated, the ultrasound probe was placed on VL and VM muscles, parallel to the muscle fascicles and perpendicular to the skin. Maps of the shear elastic modulus were obtained at 1 Hz with a spatial resolution of  $1 \times 1 \text{ mm}$ . Shear modulus was averaged in the selected circular area placed on the VL and VM (1 cm in diameter) using the Aixplorer scanner software (Q-Box<sup>TM</sup>). The selected circular area was centered to cover the greatest muscular region and avoiding aponeurosis. Height shear modulus values were recorded for each muscle to account for temporal variation. Due to extreme coefficient of variation (i.e., >20%), the values for three participants were discarded.

Finally, two squat (SJ) and counter movement (CMJ) jumps were performed. An optical measurement system (Optojump Next,

Microgate, Bolzano, Italy) measured vertical displacement of the center of gravity while participants performed two squat jumps (SJ) and two counter movement jumps (CMJ).<sup>15</sup> Thirty-second rest intervals separated each jump. Maximal performance was identified as the highest jump obtained from the two trials.

Statistical analyses were performed with Statistica software (StatSoft Inc., Tulsa, OK). All variables were normally distributed (Kolmogorov–Smirnov normality test). The intra- and inter-day reliability of mechanical, EMG and shear modulus values were assessed using the intra-class correlation (ICC, with a two-way mixed-effects model based on single rater), standard error of the mean (SEM) and coefficient of variation (CV) in the three PRE measurements (all trials pooled). As an indicator of intra-day reliability, the ICC, SEM and CV of each parameter were calculated from the control condition. For ANOVA analyses, homogeneity of variance

**Table 1**  
Intra- and inter-day reliabilities for neuromuscular measurements, shear modulus values and vertical jump performances.

	Intra-day reliability			Inter-day reliability		
	CV (%)	SEM	ICC	CV (%)	SEM	ICC
Neuromuscular measurements						
MVC (N)	2.6	18.8	0.98	3.6	10.6	0.99
RFD ( $N s^{-1} kg^{-1}$ )	10.2	20.5	0.70	13.1	15.4	0.78
VA (%)	1.0	1.1	0.85	1.3	1.0	0.87
RMS (% $M_{max}$ )	9.7	0.48	0.96	11.3	1.1	0.77
$M_{max}$ (mV)	4.0	0.69	0.98	13.3	1.6	0.89
DB (mV)	2.5	5.9	0.99	3.6	15.6	0.92
DB <sub>RFD</sub> ( $N s^{-1} kg^{-1}$ )	6.8	12.7	0.83	8.1	0.71	15.9
DB <sub>CT</sub> (ms)	5.5	3.3	0.94	7.5	3.4	0.94
DB <sub>HRT</sub> (ms)	6.7	4.4	0.94	11.3	4.7	0.93
PNS intensity (mA)				5.5	48.9	0.83
Shear modulus						
Passive VL (kPa)	4.6	1.7	0.86	7.8	3.4	0.61
Passive VM (kPa)	5.5	1.1	0.96	8.5	1.9	0.90
Vertical jump						
SJ (cm)	2.0	0.5	0.99	5.3	1.8	0.92
CMJ (cm)	1.9	0.54	0.99	4.3	1.6	0.93

MVC: maximal voluntary contraction; RFD: rate of force development; VA: voluntary activation; RMS: root mean square recorded on the vastus lateralis during a MVC;  $M_{max}$ : M-wave recorded on the relaxed vastus lateralis; DB: maximal force evoked by the potentiated doublet; DB<sub>RFD</sub>: DB rate of force development; DB<sub>CT</sub>: time to reach maximal DB; DB<sub>HRT</sub>: DB half relaxation time; PNS: peripheral nerve stimulation; SJ: squat jump; CMJ: countermovement jump; CV: coefficient of variation; SEM: standard error of the mean; ICC: intraclass correlation coefficients (two-way mixed-effect model based on single rater).

was verified by Levene's test. Two-way repeated measures ANOVAs were performed. Factors included in the statistical analysis were the condition (CON vs. ACT vs. LV) and time (PRE vs. POST). Post-hoc analyses were performed with Fisher LSD testing when the ANOVA identified significant differences. Partial eta square ( $p\eta^2$ ) was reported as an estimate of effect size, with  $p\eta^2 \geq 0.07$  and  $p\eta^2 \geq 0.14$  used as moderate and large effects, respectively.<sup>16</sup> A level of  $p < 0.05$  was used to identify statistical significance. All data are presented as mean with 95% confidence interval.

### 3. Results

Mean PNS intensities were 614 (555–672), 588 (524–650) and 591 (526–656) mA for CON, ACT and LV, respectively ( $F(2,24) = 12.1$ ;  $p = 0.24$ ;  $p\eta^2 = 0.25$ ).

Intra- and inter-day reliabilities measurements showed satisfactory results for neuromuscular, shear modulus and vertical jump (VJ) measurements (Table 1).

Table 2 presents the results for neuromuscular, shear modulus and jump measurements. No significant condition  $\times$  time interaction was found for any of these parameters ( $p > 0.05$ ).

There was a significant condition  $\times$  time interaction for muscle shear modulus recorded for relaxed VL ( $F(2,18) = 12.9$ ;  $p = 0.0003$ ;  $p\eta^2 = 0.58$ ) and VM ( $F(2,18) = 4.2$ ;  $p = 0.03$ ;  $p\eta^2 = 0.31$ ). Muscle stiffness decreased after ACT ( $p = 0.0003$  and  $p = 0.01$  for VL and VM, respectively) but it remained unchanged after CON and LV for both VL and VM ( $p = 0.10$ – $0.81$ ).

A significant condition  $\times$  time interaction was found for SJ ( $F(2,24) = 21.7$ ;  $p = 0.0006$ ;  $p\eta^2 = 0.66$ ) and CMJ ( $F(2,24) = 12.7$ ;  $p = 0.0002$ ;  $p\eta^2 = 0.53$ ). The maximal jump height recorded during SJ and CMJ significantly improved after ACT ( $p = 0.0001$  and  $0.0002$ , respectively) while no changes were reported after CON ( $p = 0.36$ – $0.81$ ).

### 4. Discussion

This study compared the acute effects of the Myovolt™, a new LV warm-up device dedicated to improve performance, with a traditional active warm-up protocol on neuromuscular performance and muscle stiffness. Our findings showed that only the active

warm-up induced higher VJ performance and decreased passive muscle stiffness of VL and VM.

The higher VJ performance following ACT is in agreement with previous results.<sup>17</sup> Despite increased VJ performance, we did not show any changes in knee extension isometric MVC, contractile properties (i.e., twitch parameters) and maximal RFD after ACT. Although it opposes previous findings of increased MVC and faster quadriceps contractile responses (i.e., twitch contraction time and half relaxation time),<sup>8,14</sup> our results are in agreement with others that showed no changes in MVC nor RFD after a cycling warm-up.<sup>18</sup> The lack of changes in RFD is further supported by our results of unchanged contractility after warm-up.<sup>19</sup> This suggests that ACT had no or minimal effect on muscle temperature (known to alter muscle contractility) or  $Ca^{2+}$  kinetics and discrepancies with aforementioned studies may be explained by differences in warm-up protocols. The absence of changes in maximal RFD and contractility after ACT is further surprising considering the significant changes reported for SJ and CMJ, is in agreement with some<sup>20</sup> but not all studies.<sup>18</sup> Addressing the increase in SJ and CMJ with no concomitant changes in quadriceps contractility and RFD increase is difficult to explain. It should be acknowledged that knee extensors are not the only muscular group that is involved in jumping performance (e.g. hip extensors, plantar flexors). It is also likely that RFD measurements did not adequately capture RFD during the jump since measurements were extracted from isometric MVC; thus, an analysis of RFD from a force plate may have been more reflective of task specificity.

In contrast, we did not find any changes in either isometric or dynamic muscle performance after LV. An increase in muscle performance has previously been reported from using the Myovolt™<sup>4</sup>; however, our results are supported by other studies that reported no changes in muscle performance after warm-up protocols that used Myovolt™<sup>3</sup> or other LV devices.<sup>6,7</sup> These equivocal results questioned LV-efficiency as a warm-up modality, while vibrating platforms have reported to improve parameters such as RFD.<sup>21</sup>

Our results revealed no change in VA or maximal EMG amplitude after LV, which is consistent with other studies that observed no changes in biceps brachii EMG following Myovolt™ warm-ups.<sup>3,4</sup> In contrast, an increased maximal EMG amplitude following LV on knee extensor muscles has been reported<sup>7,22</sup>; however EMG amplitude is a poor determinant of neural modulations.<sup>23</sup> Nevertheless,

**Table 2**  
Measurements of neuromuscular performance, muscle shear modulus and vertical jump heights before (PRE) and after (POST) a 15-min resting period (CON) and 15-min active (ACT) or local-vibration (LV) warm-up.

	Control		Active		Local vibration		Condition × time (p)
	Pre	Post	Pre	Post	Pre	Post	
Neuromuscular measurements							
MVC (N)	707.4 (631.0–783.8)	695.4 (614.3–776.5)	714.8 (639.2–790.5)	723.5 (642.4–804.4)	692.4 (621.1–753.8)	690.8 (626.1–755.5)	0.18
RFD (N s <sup>-1</sup> kg <sup>-1</sup> )	104.7 (85.6–123.7)	101.8 (79.1–124.6)	115.2 (95.8–134.5)	112.9 (98.2–127.5)	112.9 (90.5–135.2)	106.5 (90.7–122.2)	0.92
DB (mV)	280.9 (241.7–320.1)	273.7 (237.4–309.9)	284.4 (251.5–317.3)	268.9 (237.4–300.4)	284.4 (251.9–316.9)	272.1 (243.6–300.6)	0.19
DB <sub>RFD</sub> (N s <sup>-1</sup> kg <sup>-1</sup> )	115.2 (98.1–132.4)	11.3 (93.3–129.3)	125.7 (99.6–151.8)	123.2 (107.5–138.8)	110.8 (94.1–127.5)	110.5 (97.7–123.3)	0.8
DB <sub>CT</sub> (ms)	105.5 (96.6–114.3)	101.0 (91.7–110.4)	101.3 (91.5–111.1)	94.2 (85.5–102.9)	103.1 (92.1–114.2)	99.4 (87.2–111.6)	0.78
DB <sub>HRT</sub> (ms)	71.5 (60.1–83.0)	70.5 (59.2–81.8)	72.0 (60.9–83.2)	66.4 (47.1–85.7)	75.2 (64.9–85.6)	75.6 (69.0–82.3)	0.75
VA (%)	97.0 (95.3–98.6)	95.9 (93.7–97.9)	96.7 (94.6–98.7)	96.7 (94.7–98.7)	96.1 (93.1–98.9)	96.2 (94.1–98.2)	0.24
RMS (%M <sub>max</sub> )	7.8 (6.2–9.3)	7.2 (5.6–8.8)	7.6 (6.3–8.8)	6.7 (5.6–7.8)	8.0 (5.9–10.1)	7.6 (5.8–9.3)	0.44
M <sub>max</sub> (mV)	14.1 (10.8–17.3)	13.4 (10.2–16.6)	13.7 (10.5–16.8)	13.0 (9.7–16.1)	13.5 (9.8–17.2)	12.6 (9.3–15.9)	0.78
Shear modulus							
Passive VL (kPa)	10.8 (9.4–12.1)	10.6 (9.6–11.5)	10.7 (9.5–11.9)	9.0 (8.1–9.8)	11.0 (9.6–12.3)	11.6 (9.8–13.4)	<0.001
Passive VM (kPa)	7.7 (6.3–9.1)	8.0 (6.7–9.3)	8.1 (6.6–9.7)	7.3 (6.1–8.3)	7.4 (6.0–8.7)	7.6 (5.9–9.4)	0.03
Vertical jump							
SJ (cm)	29.9 (5.9–9.4)	29.4 (25.4–33.4)	30.9 (26.4–35.4)	33.5 (29.2–37.8)	29.6 (26.4–32.7)	29.7 (26.4–32.8)	<0.001
CMJ (cm)	32.6 (28.9–36.3)	32.1 (28.0–36.2)	33.7 (29.5–37.9)	35.4 (31.2–39.7)	32.6 (29.4–35.8)	32.3 (29.0–35.5)	<0.001

Data in brackets represent the mean 95% confidence interval.

MVC: maximal voluntary contraction; RFD: rate of force development; DB: maximal force evoked by the potentiated doublet; DB<sub>RFD</sub>: DB rate of force development; DB<sub>CT</sub>: time to reach maximal DB; DB<sub>HRT</sub>: DB half relaxation time; VA: voluntary activation; RMS: root mean square recorded on the vastus lateralis during a MVC; M<sub>max</sub>: M-wave recorded on the relaxed vastus lateralis; SJ: squat jump; CMJ: countermovement jump; VL: vastus lateralis; VM: vastus medialis.

based on VA and at a lower degree of EMG amplitude, it is likely that the neural effect of the current LV warm-up may have been lost due to the length of exposure time (15-min). A prolonged LV exposure (20–30 min) is thought to decrease muscle performance and maximal EMG amplitude for lower- and upper-limb muscles.<sup>5</sup> A shorter vibration duration is likely more efficient to increase central nervous excitability and thus muscle performance.<sup>7,22</sup> Discrepancy between current findings and the aforementioned studies may be explained that LV was applied to relaxed compared to contracting muscles of other studies.<sup>6,7</sup>

Furthermore, we reported no changes in VA and maximal EMG amplitude after ACT, indicating unchanged neural input of the working muscle subsequent to the warm-up. It appears inconsistent with some studies that reported an increased VA on knee extensors after active warm-up protocols.<sup>8,14</sup> Of note is the fact that our VA values recorded at baseline (96.7%) were higher than the two aforementioned studies, i.e., ~79%<sup>14</sup> and 70.0%.<sup>8</sup> Thus, the high values recorded at baseline of the present study suggest a ceiling effect, that may explain the non-significant changes in VA but also all the non-significant findings that have been previously discussed. Nonetheless, one should acknowledge that warm-up may have significant changes in less active or injured subjects.<sup>24</sup> In addition, differences in warm-up protocols may explain the discrepancies between studies.

We reported a decrease in passive muscle stiffness (–16.0 and –10.2% for VL and VM, respectively) after ACT, which is in agreement with others that observed a 23.3%<sup>25</sup> and 10.3%<sup>12</sup> decrease in hamstring stiffness following active warm-ups. Although not directly investigated in this study, the decreased muscle stiffness may be due to increased muscle temperature (although not supported by unchanged contractility) and/or a cross-bridge release induced by the active contribution of the knee extensors.<sup>12</sup> In the present study, decreases in muscle stiffness through elastography measurements were not correlated with jumping performance changes (data not shown). It is important to acknowledge that the relationship between passive muscle stiffness and performance is still largely under-investigated<sup>26,27</sup> although it has been suggested to increase RFD and power.<sup>9</sup> Although reduced passive stiffness may be an advantage for flexibility improvement,<sup>12</sup> its influence on performance cannot be clarified by the present findings. It

is possible that performance may be influenced by global musculotendinous stiffness that have been supported by findings on running economy.<sup>28</sup> Nonetheless, the non-significant changes in muscle stiffness after LV may reflect the limited effect of vibration to induce significant changes at the whole muscle that had a direct influence on passive stiffness. LV may have generated isolated modulations to a certain area of the quadriceps, which is confirmed by studies that reported changes in EMG-related parameters where vibration was locally applied to the muscle and not the synergists.<sup>29,30</sup>

With regard to the hypothesis of muscle thixotropy, it was reported that mechanical high-frequency vibration with a 2-mm amplitude applied for ~15 s to the wrist flexors induced a decrease in passive torque during passive movement. This suggests that mechanical agitation of a muscle may decrease the number of residual cross-bridges spontaneously formed at rest with some of them being separated.<sup>13</sup> One may expect similar changes after LV; however, it is likely that the very low vibration amplitudes used in current study were ineffective to induce such thixotropic changes.

## 5. Conclusions

While the present study confirms that active warm-up acutely decreased muscle passive stiffness and increased muscle performance of highly dynamic exercises, we reported no changes after LV warm-up using a newly manufactured device, i.e., Myovolt™. Considering the equivocal results on this topic, further studies are required to determine optimal parameters for warm-up using the Myovolt™ to induce significant effect that will increase performance.

## Practical implications

- A 15-min active warm-up consisting of cycling, body-weight squatting and bounding was effective to improve maximal VJ performance and decrease passive muscle stiffness of knee extensor muscles.
- Current results highlight the importance of active warm-up to decrease passive stiffness that may assist in reducing potential muscle injury.

- Further investigation is required to determine the optimal LV parameters for warm-up routines to increase muscle performance.

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