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1 The tightening parameters of the vibratory devices modify their disturbing
2 postural effects

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5 **Running title:** Balance, proprioception and tendon vibration

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19 **Abstract:**

20 The purpose was to specify the impact of two different forces exerted by vibratory devices on
21 the Achilles tendon on postural balance. The postural balance of 13 participants was evaluated
22 on a force platform in two 40s bipedal stance conditions with closed eyes. Tendon vibrations
23 (80 Hz) were triggered 10s after the beginning of the postural evaluation and applied during
24 20s. Two levels of the force exerted by the vibrators were calibrated using load cells to
25 control the tightening parameters of the vibrators: a strong tightening (ST) condition at 45 N
26 and a light tightening (LT) condition at 5 N. The soleus electromyographic (EMG) activity
27 and the spatio-temporal parameters of displacement of the centre of foot pressure (COP) were
28 analysed. To analyse the effects of the introduction, the adaptation and the end of the
29 stimulation, non-parametric tests were used. The results indicated that the soleus EMG
30 activity increased only in the ST condition. However, during the vibration the anteroposterior
31 COP position was significantly more in a backward position in the LT condition. At the end
32 of the vibration, COP parameters increased more in the LT condition than the ST condition.
33 This study demonstrated that the effects of the vibration depended on the force exerted by the
34 devices on the tendons. The ST increased the vibration effects on EMG activity through
35 greater stimulating effects compared to the LT. However, the ST could also increase the ankle
36 joint stiffness and/or somaesthetic sensory information, which attenuated the COP backward
37 shift.

38 **Keywords:**

39 Balance, postural control, vibration, proprioception, sensory manipulation, tightening

40 **Introduction**

41 Achilles tendon vibration has been widely used as a sensory manipulation to alter
42 proprioceptive afferent signals and disrupt postural balance (Maitre et al. 2015; Thompson et
43 al., 2007). Applied to the tendon via straps or elastic bands, the vibratory stimuli mainly alter
44 the activity of primary endings from muscle spindles, which may induce illusory sensations of
45 movement and alter postural balance (Roll et al., 1989; Proske and Gandevia 2012). The
46 application of the vibrator on the tendon exerts a compressive force. This force exerted by the
47 vibrator is transmitted through the tendon to the muscle, which may increase intramuscular
48 tensions. The alteration of the intramuscular tensions acts on the muscle spindle sensitivity
49 (Eklund and Hagbarth, 1966; Spiliopoulou et al. 2012) which could also influence postural
50 balance. Fusco et al. (2016) reported that when the application force on the upper limb
51 increased, the vividness, the range of motion and the duration of the illusion of movement
52 created by the vibration stimulation, may increase as well.

53 The level of the force exerted by the vibrator on the Achilles tendon may theoretically
54 influence the effects of the vibration stimulation on postural balance. Nevertheless, with the
55 exception of a few rare studies (Uimonen et al. 1996; Mildren et al. 2019; Mildren et al.
56 2017), the vast majority of experiments that have used tendon vibration to disrupt postural
57 balance did not measure nor control the tightening parameters of the vibratory device.
58 Although the force exerted on the tendon can be logically modulated under the effect of the
59 tightening parameters of the straps or elastic bands, the induced postural effects still remain
60 unknown. Hence, the aim was to specify the impact of different forces exerted by the
61 vibratory devices on the Achilles tendon on postural balance. We hypothesized that the

62 magnitude of the postural balance impairment due to the Achilles vibratory stimulation would
63 differ depending on the tightening characteristics.

64 **Materials and Methods**

65 Thirteen healthy adults (6 men, 7 women, age: 25.0 ± 9.2 years, height: 168.9 ± 6.4 cm,
66 weight: 67.8 ± 14.2 kg) free from any somatosensory, musculoskeletal and metabolic
67 disorders were recruited. All participants voluntarily signed an informed consent form before
68 starting the experiment, which was in accordance with the Helsinki Declaration. Participants
69 **had not participated in a vibration** experiment before this study and were informed about the
70 procedure.

71 Participants were instructed to stand barefoot on both legs as motionless as possible on
72 a force platform (Feetest6©, Techno Concept™, Mane, France; 40 Hz frequency, 24 bit A/D
73 conversion), with their arms crossed over their chests and their eyes closed. Their legs were
74 straight and their feet parallel (inter-malleolar distance of 14 cm). Two 40-second conditions
75 **using** different vibrator tightening parameters were tested: a light tightening (LT) condition
76 with a 5 N tightening force and a strong tightening (ST) condition with a 45 N tightening
77 force.

78 To limit the familiarisation effects with the vibration, participants performed only one
79 trial in each condition in a randomized order with a 3 minute time interval. To analyse the
80 effects of the introduction, the adaptation and the end of the vibration, the trials were
81 subdivided into 4 periods of 10 seconds. The first period (T1) was the reference situation
82 (without vibration). The second (T2) and the third (T3) periods consisted of the **intervals**

83 when the vibrations were applied. The fourth (T4) period consisted of a period with no
84 vibration.

85 Vibration was applied to the Achilles tendons (80 Hz, amplitude 0.85 mm) of both
86 legs by means of two inertial vibrators (VB 115, Techno Concept™, Mane, France) secured
87 with strap bands. The tightening force exerted by the strap bands was calibrated using two
88 force transducers (Delsey®, Paris, France) that displayed numeric force values (one for each
89 vibrator). The force transducers were fixed on support structures and connected to the strap
90 bands to control the tightening parameters (figure 1). The two tightening forces were chosen
91 to generate no discomfort and enable stability of the vibrators on the Achilles tendon while
92 representing two different tightening forces for clinicians and participants.

93 The centre of foot pressure (COP) position (figure 2) was recorded with a force
94 platform. COP signals were filtered using a fourth-order Butterworth low-pass filter with a 12
95 Hz cut-off frequency. The COP surface (90% prediction ellipse area) and the mean COP
96 velocity along the mediolateral (ML) and anteroposterior (AP) axes were then calculated as
97 indicators of participants' postural balance (Paillard and Noé, 2015). The mean
98 anteroposterior COP position was calculated to provide information about a vibration-induced
99 backward postural shift.

100 Surface electromyographic (EMG) activity of the soleus (SOL) was recorded at 1000
101 Hz (CMMR > 100 dB; input impedance 1 MΩ) with the Powerlab 16/35 data acquisition
102 system (ADInstruments, Castle Hill, Australia) with a resolution of 16 bits using a ×1000
103 g.BSamp biosignal amplifier (g.tec, Schiedlberg, Austria). Electrodes were placed according
104 to SENIAM's guidelines (Hermens et al., 2000) on the left leg. EMG signals were filtered

105 using a Butterworth Bandpass filter (10 - 450 Hz) and a notch filter centred at the vibration
106 frequency (80 Hz). The RMS values were then computed from filtered EMG signals.

107 To determine how participants adapt their postural balance depending on the
108 experimental conditions, the absolute changes between two consecutive measurement periods
109 were calculated for all the parameters as follows:

$$110 \qquad \qquad \qquad \text{Absolute increase} = (T_{n+1} - T_n)$$

111 The absolute increases characterise postural behavioural changes when vibration was
112 introduced (T1 to T2), during the vibration (T2 to T3) and at the end of the vibration (T3 to
113 T4). All signals were processed with MatlabR2015a software (The Mathworks Inc., Natick,
114 USA).

115 *Statistical analysis*

116 Statistical analyses were performed with R statistical software. The normal distribution of
117 data was checked using Shapiro-Wilk tests. Because normality was skewed in most cases, **the**
118 **data was** compared using non-parametric tests. Differences among repeated measures (T1, T2,
119 T3, T4) for the COP and EMG parameters were tested for each condition using the Friedman
120 test. When significant effects occurred, pairwise comparisons were performed with the
121 Nemenyi test (Demšar, 2006). Differences between LT and ST conditions were tested using a
122 Wilcoxon signed rank test for all the parameters and for their absolute increases (T1 to T2, T2
123 to T3, T3 to T4) at each corresponding time period. The level of significance was set at $p <$
124 0.05.

125 **Results**

126 *COP displacement parameters*

127 The results showed that the COP surface and velocities (AP and ML) increased when
128 participants were subjected to vibration in both conditions compared to the reference situation
129 (T1) (figures 3A, 4A and 4C). During the stimulation (T2 and T3), the anteroposterior COP
130 position was more backward in the LT than in the ST condition (figures 2 and 5).

131 When the stimulation stopped, the COP surface and velocities were higher at T4
132 compared to T1, whatever the tightening conditions (figures 3A, 4A and 4C). Nevertheless,
133 the COP parameters evolve differently depending on the tightening conditions. Indeed, the
134 absolute increases (T3 to T4) of the COP surface and the COP velocities (figures 3B, 4B and
135 4D) were significantly more important in the LT than in the ST condition. Moreover, the COP
136 surface and the COP velocities (figures 3A, 4A and 4C) were higher at T4 than at T3 only in
137 the LT condition. Otherwise, the COP surface (figure 3A) and the COP ML velocity (figure
138 4C) were higher at T4 in the LT than in the ST condition. Concerning the COP position, the
139 anteroposterior COP position was more forward at T4 than at T3 only in the LT condition
140 (figure 5A) and the absolute increase (T3 to T4) was higher in the LT than in ST condition
141 (figure 5B).

142 *EMG activity*

143 The SOL EMG activity (figure 6A) increased between T1 and T2 only in the ST condition.
144 The absolute increase of the SOL EMG activity (figure 6B), at the start of the stimulation (T1
145 to T2), was more important in the ST than in the LT condition. In addition, the SOL EMG
146 activity was higher at T2 and T3 in the ST than in the LT condition (figure 6A).

147 **Discussion**

148 The aim was to specify the impact of different forces exerted by the vibratory devices on the
149 Achilles tendon and its effect on postural balance. The main results indicated that the effects
150 of the vibration on the EMG and the COP parameters depended on the force exerted by the
151 devices on the Achilles tendons.

152 At the start of the vibration, only the EMG activity showed evidence of a difference
153 between the two conditions. The SOL EMG activity increased only in the ST condition
154 (figure 6A). In addition, the SOL EMG absolute increase (T1 to T2) as well as the SOL EMG
155 values at T2 and T3 (figures 6B and 6A) were higher in the ST than in the LT condition.
156 These results indicated that the soleus EMG response was stronger for the ST than for the LT.
157 The **stronger** effect observed on the soleus EMG for the ST, could be linked to the mechanical
158 constraints induced by the application of the vibratory devices on the tendon. Firstly, the more
159 important pressure exerted by the vibrators on the tendon may have participated in increasing
160 intramuscular tension and altered the sensitivity of the soleus muscle spindles to the stimuli.
161 Indeed, Cordo et al. (1993) reported that the sensitivity of the muscle afferents to tendon
162 vibration **can** be critically influenced by the force applied perpendicularly by the device.
163 Secondly, the pressure exerted by the devices in contact with the skin created local distortions
164 depending on the tightening parameters used. In the ST condition, the pressure exerted by the
165 vibrator extended the distortion and increased the contact area on the tendon compared to the
166 LT condition. Previous studies reported that the vibrotactile sensation is dependent on the
167 skin-device contact area (Forta et al., 2012; Pereira et al., 2016). It is likely that a ST
168 increased the number of tendon fibres in contact with the vibrator, which participated in the
169 increase in the number of mecanoreceptors stimulated. Thirdly, the stronger pressure exerted

170 on the tendon by the ST may have influenced the transmission of the vibration wave. Indeed,
171 Pyykko et al. (1976) demonstrated that when the pressure against the vibrator increased the
172 transmission of the vibration increased. While the soleus EMG increased in the ST condition,
173 no significant increase was detected in the LT condition (figure 6A). This result suggests that
174 the LT could not provide enough pressure on the tendon to generate a clear soleus response
175 for all the participants. However, the COP surface and velocities increased in both conditions,
176 indicating a significant effect of the stimulation (figures 3 and 4). Otherwise, the
177 anteroposterior COP position at T2 and T3, were more backward in the LT than in the ST
178 condition (figure 5A). In addition, strong tendencies ($p = 0.06$) argued that the anteroposterior
179 COP position would shift backward more in the LT than in the ST condition (figures 5A and
180 5B). Thus, the vibration also altered proprioception in the LT condition and probably
181 provoked a backward shift in the LT condition through a complex multi-segmented postural
182 response rather than a localised soleus response. Otherwise, these results could suggest that,
183 although the ST increased the soleus EMG response to the tendon vibration, the ST reduced
184 the backward influence of the Achille tendon vibration on the COP position. This effect had
185 also been observed at the end of the vibration and may be explained by analysing the postural
186 parameters of this corresponding time period (cf., paragraph below).

187 As previously demonstrated, the reweighting of proprioceptive sensory information
188 induced postural movements mainly in the anteroposterior direction at the end of the vibration
189 (Thompson et al., 2007; Hayashi et al. 1981). In the present study, the COP surface and the
190 COP ML and AP velocities were higher at T4 than at T1 in both conditions (figures 3A, 4A
191 and 4C). These results indicated that postural balance was disrupted at the end of the
192 stimulation. However, the evolution of all the COP parameters differed according to the

193 tightening conditions. The absolute increase (T3 to T4) of the COP surface and velocities
194 were higher in the LT than in the ST condition (figures 3B, 4B and 4D). The anteroposterior
195 COP position was significantly different between T3 and T4 only in the LT condition (figure
196 5A). In addition, the absolute increase (T3 to T4) of the anteroposterior COP position was
197 more important in the LT than in the ST condition. These results illustrate that the end of the
198 stimulation was less disrupting in the ST than in the LT condition. It seems clear that the
199 more important postural balance alteration of the end of the vibration was linked to the COP
200 position adopted. The more backward the COP position during the vibration the more the
201 postural disturbance/readjustment at the end of the stimulation. The intriguing result of the
202 present study was that, although the postural balance was altered during and after the
203 vibration (figures 3 and 4), there was no significant evolution of the anteroposterior COP
204 position in the ST condition (figure 5). This could be explained by the fact that the strong
205 pressure exerted by the vibrator, acting on musculotendinous tension, increased the passive
206 ankle stiffness. The ankle stiffness plays a significant contribution in the ability to maintain
207 postural balance (Winter et al., 1998). The Achilles tendon is a main contributor to the
208 intrinsic ankle stiffness (Sakanaka et al., 2018). Tendon stiffness is dependent on the linkage
209 between the collagen molecules, cross-linked end-to-end within a fibril and it increases with
210 the tension that it transmits (Sakanaka et al., 2018). In the present study, it is likely that the
211 transmission of the force exerted by the strong tightening of the devices on the Achilles
212 tendon participated in increasing the tension/stretch between the collagen fibrils, which could
213 passively increase the tendon stiffness. Moreover, the increase in external passive stiffness
214 can contribute to improving postural balance (Warnica et al. 2014). The ST of the device
215 setup (the strap bands, the load cells' support structures and the vibrators) would increase the
216 pressure of the underlying structures more than the LT. We cannot exclude that a stronger

217 pressure exerted on the underlying structures around the ankle joint may partly limit/reduce
218 the ankle movement. With the ST, the devices could act as mechanically efficient external
219 supports against gravitational destabilizing torque. In addition, the stronger pressure, in the
220 ST condition, could amplify the afferent information from mechanoreceptors **underneath the**
221 **devices** more than in the LT condition (Ghai et al. 2017). Consequently, the ST might have
222 enhanced somaesthetic afferents by increasing the proprio-cutaneous stimulation over the
223 ankle. Hence, the ST could participate in reducing anteroposterior disturbance during and
224 after the stimulation due to **a** higher passive ankle stiffness and/or an increase of the
225 somaesthetic acuity.

226 In conclusion, the tightening parameters can alter postural balance during and after the
227 vibratory stimulation. The ST increased the effects of the vibration on the EMG activity
228 through greater stimulating effects compared to the LT. However, the vibration stimulation
229 effects on postural balance could be attenuated because of increases in ankle stiffness and/or
230 in somaesthetic sensory information provided by the ST. As suggested by Ferrari et al.
231 (2019), a complete control of the stimulation parameters is crucial to compare results among
232 participants of different studies when using vibration stimulation. **Tightening parameters**
233 **should not be excessively strong, to avoid altering biomechanical properties of the tissues**
234 **underneath the device.**

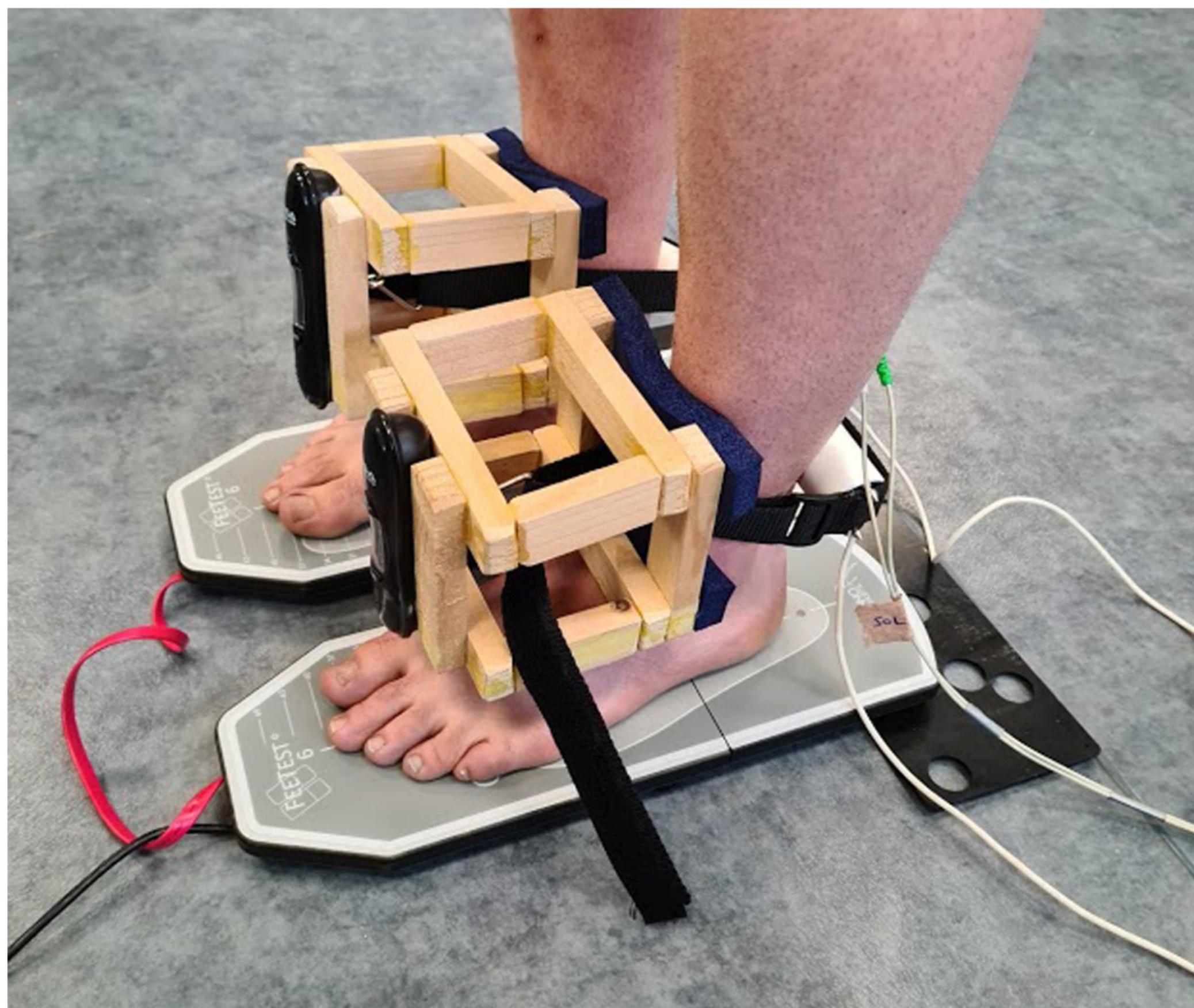
235 **Conflict of Interest Statement**

236 The authors declare that they have no known competing financial interests or personal
237 relationships that could have appeared to influence the work reported in this paper.

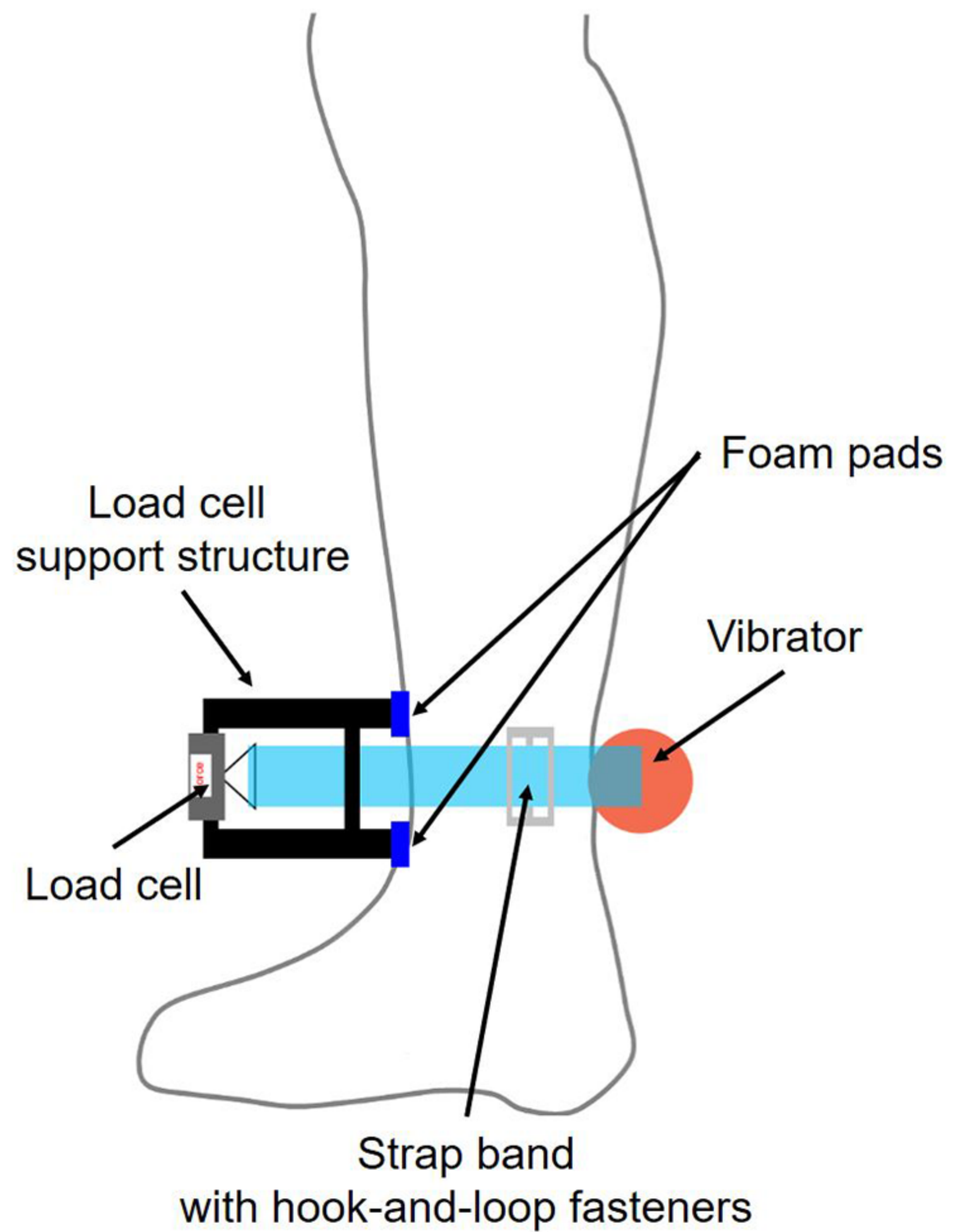
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A



B

Light tightening condition Strong tightening condition

