Effects of noxious stimulation to the back or calf muscles on gait stability

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1. Introduction

Stable walking without undue fall risk requires appropriate control to deal with perturbations that originate in the external environment and inside the body (Bruijn et al., 2013; Toebes et al., 2012). As a result of impaired sensorimotor control, reduced gait stability is associated with aging (Kang and Dingwell, 2008) and neurological disorders (Jinnker and Lamoth, 2012; Reynard et al., 2014). Musculoskeletal pain has been associated with fall risk (Asai et al., 2015; de Zwart et al., 2015; Kitayuguchi et al., 2015) and may also impact stability. For example, spinal movement stability was lower during pain than no pain (Ross et al., 2015). It is important to address the effects of pain on gait stability as musculoskeletal pain increases with age (Hoy et al., 2014; Smith et al., 2014), which potentially could increase falls risk (Foley et al., 2006; Leveille et al., 2009).

Motor adaptations to pain are thought to protect the painful/injured tissues (Hodges and Tucker, 2011; Lund et al., 2011; van Dieën et al., 2003). Such adaptations are thought to increase joint stiffness (Hodges et al., 2013; van den Hoorn et al., 2012) and could potentially enhance stability. However, increased stiffness may coincide with reduced responsiveness. In addition, nociceptive input may impair proprioceptive acuity (Brumagne et al., 2000; Lee et al., 2010; Matte et al., 2002) and force regulation (Descarreaux et al., 2005; Salomoni et al., 2013) which could reduce stability. The effect of pain on gait stability is likely to depend on the region that is painful and, if muscle is painful, on its biomechanical role in gait. The calf muscle–tendon unit is thought to be the principal contributor to propulsion/push-off, but also to contribute to frontal plane movements (Kim and Collins, 2015; Pandy and Andriacchi, 2010). Back muscles control trunk orientation by counteracting movements, such as those induced by push-off and...
walking speeds; 0.94 ms

3. Results

3.1. Pain intensity

During LBP, the average pain intensities were 4.9 ± 1.7 and 4.5 ± 2.1 at 0.94 ms⁻¹ and at 1.67 ms⁻¹, respectively. During CalP,
the average pain intensities were 5.4 ± 1.5 and 4.8 ± 1.9 at 0.94 ms⁻¹ and at 1.67 ms⁻¹, respectively. Pain intensity was not significantly different between locations (F=2.00 and P=0.18), but was lower at 1.67 ms⁻¹ than at 0.94 ms⁻¹ (F=4.49 and P=0.05). Pain was restricted to the area around the site of hypertonic saline injection.

### 3.2. Temporal gait parameters

#### 3.2.1. LBP

Stride time was shorter during LBP than control at 0.94 ms⁻¹, but not at 1.67 ms⁻¹ (see Table 1 for F-statistics and corresponding P-values (Fig. 1)). Independent of speed, stance time of both legs was shorter during LBP than control. Swing time of the left, but not right leg was shorter during LBP than control. Stance and swing time were not significantly different between left and right legs during LBP.

During washout LBP, stance time of both legs was not significantly different from control, but swing time duration of both legs was longer than control.

#### 3.2.2. CalfP

Stride time was shorter during CalfP than control at both speeds (Fig. 1) and was not significantly different from control during washout CalfP. Left and right leg (painful leg) stance time and swing time of the left but not right leg was significantly shorter during CalfP than control. During CalfP, right leg stance time was shorter and swing time was longer than the left leg. Together, these findings can be interpreted as “limping” during CalfP.

During washout CalfP, stance time was not significantly different from control of either leg, but right leg swing time was longer. During control, right leg stance time was longer and right leg swing time was shorter than the left leg. The use of the right leg for recording of muscle activity may have contributed to this observation and may imply that we underestimated the effect of CalfP on this parameter.

### 3.3. Thorax movement

#### 3.3.1. Maximum Lyapunov exponent (LDE)

3.3.1.1. LBP. During LBP, independent of movement axes, gait stability was lower (LDEs were higher) than control when participants walked at 0.94 ms⁻¹, and LDEs were similar to control values during washout LBP (see Table 2 for F-statistics and corresponding P-values (Fig. 2)). In contrast, at 1.67 ms⁻¹ gait stability was higher (LDEs were lower) during both LBP and washout LBP than control.

3.3.1.2. CalfP. With CalfP, gait stability was lower (LDEs were higher) than control at 0.94 ms⁻¹ (Fig. 2), but CalfP did not affect LDE significantly when participants walked at 1.67 ms⁻¹. At both speeds, LDEs were not significantly different from control during washout CalfP. Gait stability was lower (LDEs were higher) with CalfP than LBP at both walking speeds.

#### 3.3.2. Magnitude and variability

3.3.2.1. LBP. LBP did not significantly affect thorax RMS along any of the axes (Table 2 and Fig. 3). However, RMS along the VT axis was higher during washout LBP than during control. Along all axes at 0.94 ms⁻¹, SDs were greater during LBP than control (Table 2 and Fig. 3), and were not significantly different from control during washout LBP at this speed. In contrast, at 1.67 ms⁻¹ SDs were lower than control during both LBP and washout LBP.

3.3.2.2. CalfP. With CalfP, independent of speed, thorax RMS along the ML axis was larger than control (Table 2 and Fig. 3), but was not significantly different from control during washout CalfP. RMS along AP and VT axes was not affected by CalfP. However, during washout CalfP, RMS along both of these axes was larger than control. RMS along the ML axis was larger with CalfP than LBP. RMS along the AP and VT axes were not significantly different between the pain conditions.

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**Table 1**

Results of repeated measures ANOVA of temporal gait parameters.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Condition</th>
<th>Speed</th>
<th>Condition × speed</th>
<th>Side</th>
<th>Condition × side</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>F-value</td>
<td>P-value</td>
<td>F-value</td>
<td>P-value</td>
</tr>
<tr>
<td>Stride time</td>
<td>LBP</td>
<td>11.07</td>
<td>&lt; 0.001</td>
<td>426.06</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Stance time</td>
<td>LBP</td>
<td>9.26</td>
<td>&lt; 0.001</td>
<td>453.17</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Swing time</td>
<td>LBP</td>
<td>11.22</td>
<td>&lt; 0.001</td>
<td>236.57</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>

**Condition × speed post-hoc**

<table>
<thead>
<tr>
<th>Speed 1 (0.94 ms⁻¹)</th>
<th>Control vs. LBP</th>
<th>LBP vs. CalfP</th>
<th>Left leg vs. Control vs. Right leg vs. Control</th>
<th>LBP vs. CalFP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stride time</td>
<td>F-value</td>
<td>P-value</td>
<td>F-value</td>
<td>P-value</td>
</tr>
<tr>
<td>LBP</td>
<td>0.001</td>
<td>0.46</td>
<td>CalFP</td>
<td>0.001</td>
</tr>
<tr>
<td>LBP</td>
<td>0.001</td>
<td>0.26</td>
<td>LBP</td>
<td>1</td>
</tr>
<tr>
<td>Stride time</td>
<td>0.82</td>
<td>1</td>
<td>CalFP</td>
<td>0.001</td>
</tr>
<tr>
<td>LBP</td>
<td>1</td>
<td>LBP</td>
<td>CalFP</td>
<td>1</td>
</tr>
<tr>
<td>Stance time</td>
<td>1</td>
<td>&lt; 0.001</td>
<td>1</td>
<td>0.01</td>
</tr>
<tr>
<td>Swing time</td>
<td>1</td>
<td>&lt; 0.001</td>
<td>0.71</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Stance time</td>
<td>1</td>
<td>&lt; 0.001</td>
<td>0.07</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Swing time</td>
<td>1</td>
<td>&lt; 0.001</td>
<td>0.07</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>
4. Discussion

Partially consistent with our first hypothesis, the results of this study show that nociceptive irritation of a calf or back muscle reduces gait stability at low walking speed. Consistent with the second hypothesis, the results show that the effects of pain on gait stability are larger for calf pain than LBP. Somewhat unexpectedly, these effects were not found at high walking speed, and for LBP even reversed. These differences might be explained by different objectives of motor adaptation with different tasks and differences in biomechanics.

4.1. Why does pain affect gait stability?

Broadly, changes in movement during pain have been considered to reflect either adaptations that serve to protect the painful tissue, or arise from negative consequences secondary to the nociceptive stimulation. In both cases, the expression of adaptation is likely to be molded by pain intensity, past experiences, perceived threat, pain beliefs, context and task constraints (e.g., Hodges and Tucker (2011) and Moseley and Arntz (2007)). In the case of the former, it is assumed that adaptations will modify load on the painful structure (e.g. limit movement amplitude, or contraction intensity). In the case of the latter, mechanisms at multiple nervous system levels enable pain to interfere with motor function, including the effects of nociceptor activation on motor-neurons (Iggo, 1961; Paintal, 1960) and effects at the motor cortex (Martin et al., 2008; Tsao et al., 2008). Changes in gait stability observed in the present study can be interpreted with respect to these different processes. This interpretation is not straightforward and depends on the location of pain (injected muscle) and gait speed.

4.2. Effect of LBP on gait stability

LBP changed gait stability at both walking speeds, but the effect was opposite for each. The difference between speeds might be explained by different values placed on the pain in each context. For instance, at the faster speed, where forces and muscle activation are greater, and the potential consequence of perturbations is also greater, pain may lead the nervous system to optimize control of gait stability. At the slower speed where the potential consequence of perturbation is less, pain may be less important and induce less adaptation of control. This hypothesis is supported by the observation of greater variability at the slower speed, but less variability at the faster speed during LBP. Lower thorax variability during LBP at the faster speed might reflect a protective neuromuscular control strategy with the objective to enhance attenuation of perturbations between the pelvis and thorax, as reflected by the greater gait stability, potentially as a result of enhanced trunk stiffness. Ross et al. (2015) did observe a positive relation between trunk stiffness and stability (LDE) of spinal movements during a flexion-extension task, however on average trunk stiffness decreased with pain in this study. Increased gait stability with LBP at the faster speed could lead to more predictable trunk movements. This might be necessary to compensate for the potential of altered proprioception due to pain (Matre et al., 2002), and/or less effective corrective strategies (Mok et al., 2007). Although increased stiffness may be successful for control of small amplitude perturbations experienced in the predictable task of treadmill walking as tested here, it may limit the potential for control and recovery from larger perturbations (Mok and Hodges, 2013).

4.3. Effect of calf pain on gait stability

In line with our hypothesis, CalfP reduced gait stability at the slower speed. Further, at the slower speed CalfP affected gait stability more than LBP. Adaptations to pain depend on the muscle that is the source of nociceptive input (Hug et al., 2014). Because of the critical role they play in gait, any adaptation to calf muscle function is likely to have a greater effect on gait features, such as gait stability, than changes to back muscles. In addition to their primary role in propulsion, calf muscle activity is a key determinant of walking speed, vertical support (Anderson and Pandy, 2003; Ellis et al., 2014) and mediolateral balance (Kim and Collins,
hip flexor muscle activity and greater flexion-extension ROM between the pelvis and thorax in association with reduced calf muscle activity and limping (van den Hoorn et al., 2015). Although such changes may retain overall task objective, our data suggest that these adaptations reduced gait stability.

Contrary to our hypothesis, CalP did not affect gait stability at the faster speed. Although thorax velocity along ML was greater during CalP, and features consistent with limping were observed, thorax variability and stability were not affected. This implies that a different adaptation was adopted at the faster speed. Consistent with earlier arguments, this could be explained by the tighter constraint of walking at this speed, secondary to the greater potential for task failure from even minor disturbances. Other data support the tighter constraint of gait at faster speeds. For instance, inter-limb coordination improves with speed and has been related to improved ability to recover after perturbations (Krasovsky et al., 2014). Perturbations assessed in our study are small naturally occurring disturbances and are distinctly different from the large trip-inducing perturbation used by Krasovsky et al. (2014), therefore direct comparison is difficult. Although we imply enhanced active control of perturbations, simple mechanics could also explain the results. For instance, the greater momentum of the faster moving limbs could improve attenuation of perturbations, and the greater relative contribution of the force generated by the release of the stored energy in the muscle–tendon complex (passive recoil) at faster walking speeds (Hof et al., 1983; Lai et al., 2015; Lichtwark et al., 2007) could lead to a reduced sensitivity of gait kinematics to changes in calf muscle activation. Taken together, greater demand for tighter control of gait and the beneficial effect of changed mechanics at faster speeds could explain why CalP did not have major impact on gait stability.

4.4. Implications

Reduced gait stability at lower speeds with experimental pain could have implications for older people at high risk of falls. Musculoskeletal pain in this population has been linked to falls (Asai et al., 2015; de Zwart et al., 2015; Kitayuguchi et al., 2015), and the...
results of the present study imply this might, at least in part, be explained by the negative effect that musculoskeletal pain has on gait stability. Although the average age of participants in the current study was young and pain was induced experimentally, it allowed examination of the effect of pain in isolation. Many factors could contribute to reduced gait stability in the elderly and musculoskeletal pain might be one of these factors. Future investigations are needed to investigate the potential relationship between muscle pain, gait stability and falls risk in older people.

**Conflict of interest statement**

The authors declare no conflicts of interest, financial or otherwise.

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