Investigating the Effects of Pain Priming and Cognitive Distraction on Walking of Lower Back Pain Sufferers by Motion Capture

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Abstract

Chronic lower back pain (LBP) is a significant medical and financial problem that affects individual's physical, psychological, and social wellbeing, and is costly for the society. Physical rehabilitation is routinely applied in treatment, but poor compliance to therapeutic self-exercises remains a problem. Technological solutions with supportive human–computer interactions could aid the rehabilitation of lower back pain patients. We were interested in effects that in such user interfaces could arise from priming, i.e. the automatic activation of behavioural representations by environmental stimuli. Merely solving scrambled sentence tasks with words associated to old age has been reported to reduce the walking speed of participants (Bargh, Chen & Burrows, 1996). We hypothesized that priming participants who had previously experienced LBP with concepts related to pain would induce similar changes in walking of the participants as has been reported for LBP patients (Clarke & Eccleston, 2009). We expected that these changes should not be observed during cognitive distraction for cognitive distraction has been reported to shift the walking behaviour of LBP patients towards normal (Van der Hulst, Vollenbroek-Hutten, Schreuers, Rietman & Hermens, 2010). We assessed the walking characteristics of the participants (N=23, age 18–65, 9 males, 14 females, all UCL students or staff members) by motion capture after pain priming, during cognitive distraction, and without manipulation (control condition). No statistically significant effects of the condition on the recorded walking characteristics could de demonstrated.

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Introduction

Pharmaceutical, surgical, physical and psychological therapies have been applied to alleviate the suffering of the chronic lower back pain (LBP) patients. Yet, despite these interventions, complete recovery is seldom achieved (Andersson, 1999; Elliott, Smith, Hannaford & Chambers, 2002). Altered muscle activation patterns, stability, posture, trajectories, and response to load observed in LBP patients have been suggested to contribute to the pathogenesis of chronic lower back pain, leading to prolonged pain, recurrent pain episodes, functional disabilities, and other musculoskeletal problems due to altered load (Shum, Crosbie, Lee, & 2005; Silfies, Bhattacharya, Biely, Smith, & Giszter, 2009). New technology to aid in chronic pain rehabilitation could potentially significantly supplement, support, and reinvent the current rehabilitation approaches. Computer-based motion capture systems could give feedback to the patients, guiding them to do the physiotherapy exercises correctly. In order to be effective, the human–computer interactions of any such new technology should be optimized to persuade the patients to use it. This is important since patient compliance remains as a major problem in conventional interventions – and traditional attempts to increase patient compliance have only small long-term effects (Kerns & Rosenberg, 2000; van Middelkoop, Rubinstein, Kuijpers, Verhagen, Ostelo, Koes, & van Tulder, 2011; van Dulmen, Sluijs, van Dijk, de Ridder, Heerdink & Bensing, 2007; Mayoux-Benhamou, Giraudet-Le Quintrec, Ravaud, Champion, Dernis, Zerkak, Roy, Kahan, Revel & Dougados, 2008).

The pain itself and fear of pain and further injury affect how the LBP patients move, but numerous things affect the way people in general move: individual differences, mood, attention, context and social situation (Clarke & Eccleston, 2009; Johnson, 2005; Leeuw, Houben, Severeijns, Picavet, Schouten & Vlayen, 2007; Wallbott, 1998). A surprising effect is that small environmental stimuli can automatically activate behavioural representations, priming humans to behave in certain

ways (Bargh, Chen & Burrows, 1996; Bargh & Chartrand, 1999; Dijksterhuis & Bargh, 2001; Dijksterhuis & van Knippenberg, 1998). For example, merely reading words related to the elderly primes young people to walk slower (Bargh, Chen & Burrows, 1996). Potentially, reminding the patients' of their pain during clinical rehabilitation exercises or experiments could also affect the way they move through priming: the automatic activation of the modes of movement associated to pain.

We hypothesized that priming participants who had previously experienced back pain with concepts related to back pain would induce the participants to move in way observed in people with current back pain, i.e. in a slower and in a more guarded manner. Since cognitive distraction has been shown to normalize muscle activation patterns in chronic lower back pain patients during walking (Van der Hulst, Vollenbroek-Hutten, Schreuers, Rietman & Hermens, 2010), we hypothesized that it should lead to more normal walking behaviour. The current study investigated these effects in participants who had suffered from back pain, but who were not currently experiencing chronic low back pain.

Literature review

The burden of lower back pain on the individuals and the society as whole, the current therapeutic interventions and the potential role of HCI technology in such interventions are first described, as these provide the motivation for the present study. In particular the potential induction of priming and cognitive distraction effects in pain-related HCI technology motivated the present study. The key hypothesis was that priming would induce the participants move in a way associated to low back pain, and that cognitive distraction would normalize the way the participants move. Accordingly, the effects of low back pain on movement and the communicative role of pain expression are reviewed, as well as the literature on priming and the effects of cognitive distraction.

Lower back pain interferes with individual's wellbeing and places heavy burden on society

According to International Association for the Study of Pain pain is "an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage" (IASP, 2007). The British Pain Society defines chronic pain as long-term pain that lasts more than 12 weeks or continues after the expected time of healing (The British Pain Society, 2010). Pain that continues after healing process has no apparent survival value. Instead, it affects negatively virtually all human activities, including such necessities as eating and sleeping; hence it often leads to mental and physical exhaustion (Breivik, Collett, Ventafridda, Cohen & Gallacher, 2006; Solberg Nes, Roach & Segerstrom, 2009). Chronic pain can lead to changes in cortical function, chronic disability, and changes in movement and posture (Gatchel, Polatin, Noe, Gardea, Pulliam & Thompson, 2003; Vartiainen, 2009; Malinen, Vartiainen, Hlushchuck, Koskinen, Ramkumar, Fors, Kalso & Hari, 2010).

The estimates on the prevalence of chronic pain depend strongly on the study and the definition used (Verhaak, Kerssens, Dekker, Sorbi, & Bensing, 1998). One study that probed yearly prevalence of chronic back pain (back pain of >100 days within preceding year) reported 9% prevalence of chronic back pain in general adult (≥18 y.) population (Sternbach, 1986). The total cost of chronic lower back pain is difficult if not impossible to evaluate, since it should include not only the cost of treatment, disabilities, social benefits, and inability to work, but also e.g. decreased productivity at work. The direct cost of treating lower back pain for NHS was approx. 1.6 billion pounds in 1998 (Maniadakis & Gray, 2000). Chronic back pain alone results in disability, incapacity, and related benefits of ~5 billion pounds per year in UK (British Pain Society, 2010).

The burden the chronic LBP places on both the society and the people provides an impetus to better understand the processes involved in chronic LBP and its rehabilitation.

Therapeutic interventions to pain and a potential role for HCI technology

To elucidate the potential role of HCI technology, priming, and cognitive distraction in LBP management the current approaches to treat pain and their limitations will be briefly reviewed; these approaches include pharmaceutical, surgical, psychological, social, technological, and physical rehabilitation interventions.

Pharmaceuticals are usually the first line intervention against pain. Modern pharmaceuticals can often only reduce the level of pain, and, importantly, these pharmaceuticals come with significant adverse effects (Vonkeman & Laar, 2010; Dworkin et al., 2007). Surgical treatments can aid some carefully selected patients, but they involve considerable risks. Surgical treatments include treatments to stabilize the affected region (such as stiffening a joint) and approaches that involve technology, such as deep-brain and spinal cord stimulators (Kringelbach et al., 2007; North, Kidd, Farrokhi & Piantadosi, 2005). Psychological interventions, such as cognitive behavioural therapy, are widely applied, but their achievement is mainly to help the individual to make adjustments to his/her life and cognitions so that the pain and living with it becomes more acceptable, manageable and bearable (Gatchel & Rollins, 2008). Unfortunately, psychological therapy is expensive, limited in availability, and cannot normally continue to the distant future.

In treatment of chronic pain involving musculoskeletal component physical rehabilitation is routinely used, e.g. to strengthen the muscles to stabilize the region, to prevent painful movements under load bearing, and to improve mobility and preserve the functionality of the affected region. Physical therapy other than exercises performed

by the patient himself does not appear to be useful in treatment of chronic LBP, and the response of patients to exercises appears variable (Airaksinen et al., 2005) – this variability may be related to the etiologies and particular pathophysiologies of the patients' conditions as well as patient compliance to exercises.

Any single form of therapy has limited efficacy. Intensive, daily, extensive (>100 h), multidisciplinary, holistic approaches have been shown to be more effective than conventional, therapies, such as a mere combination of pharmaceuticals and physiotherapy (Guzman et al., 2001), whereas less extensive (<100 h) multidisciplinary approaches appear to offer no benefits compared to pharmaceuticals and physiotherapy alone (Kääpä, Frantsi, Sarna & Malmivaara, 2006; Guzman et al., 2001).

Although intensive multidisciplinary intervention programmes can significantly improve the situation which the individual is in, they are expensive, and still leave room for improvement in pain management. One potential limitation is the compliance of the pain patients. Because of the effort involved in doing the exercises and maintaining the new behavioural models as well as because of fears regarding adverse effects of drugs and perhaps due to the lack of immediate relief from pain, many of the patients do not follow instructions (Kerns & Rosenberg, 2000; van Middelkoop, Rubinstein, Kuijpers, Verhagen, Ostelo, Koes, & van Tulder, 2011); the compliance particularly for home-based exercises can be surprisingly poor – e.g. Mayoux-Benhamou et al. (2008) found that after six months even with interventions to support compliance only 13.5% of rheumatoid arthritis patients did ≥30% of prescribed exercises.

Though currently the use of technological interventions is limited, they could significantly support pain management. Immersing, cognitively distracting virtual reality environments in particular have been proposed to be effective in reducing pain (Hoffman et al., 2011). Technological interventions have also been used to support physiotherapy. The use of technology in physical therapy includes both e.g. a simple

biofeedback system that helps to normalize trunk position (Davis, Carpenter, Tschanz, Meyes, Debrunner, Burger, & Allum, 2010) as well as video game-based approaches that attempt to achieve good compliance and controlled exercises; the latter include systems for balance exercises (Betker, Szturm, Moussavi, & Nett, 2006) and for lower back pain therapeutic exercises (ValedoMotion brochure, 2011). In the ValedoMotion by the Swiss company Hocomo the system monitors the movement of lower back, and the patient plays a computer game by moving his back. The most useful approach could be to use immersing cognitive distraction during therapeutic exercises, relieving possible pain during exercises, and a system that encourages and entices the patients to perform the exercises and ensures that the exercises are performed correctly. Although there is currently no evidence for the usefulness of such an approach, there is evidence demonstrating that physioterapist-guided therapeutic exercises and conventional physiotherapy are more effective and more cost-effective than unsupervised self-exercise (Torstensen et al., 1998), implying that either not all the exercise is equal or that the compliance to self-exercise is poor.

The potential effects of priming and cognitive distraction are of interest from the perspective of human–computer interactions design for the technology used in rehabilitation. If priming with pain increases the effects of pain on the kinematics, then any interactive technology should try to avoid reminding the patients about their pain. If the pain-related movements in walking could be identified and if sufficiently inexpensive motion capture equipment becomes available, then cognitive distraction could be targeted by the system to those occasions when the patient appears to be in or focused on pain. In the present study our aim was to assess the potential effects of priming and cognitive distraction on the walking of currently pain-free participants with previous experience of back pain.

Lower back pain results in more guarded and stiff movements with altered muscle activation patterns

Since we hypothesize that priming could induce the participants to move in a way associated to pain, it is of key interest that people with lower back pain have been found to alter their movements and posture. Some of these changes should be observable by means of motion capture, and hence could also allow for monitoring of the effectiveness of rehabilitation as well as recognition of pain by an interactive system. The changes resulting from LBP could be expected to be very variable, as chronic LBP is a heterogenous condition that can originate from bones, muscles, ligaments, nerves, or other soft tissues, and therefore is likely to affect the posture and movement differently depending on the site and the mechanism of the injury / pain. Certain types of movement adjustments, however, have been linked to LBP patients in earlier studies. It has also been demonstrated that these movement adjustments tend to persist in people who have experienced an episode of LBP but who are currently pain free (MacDonald, Moseley & Hodges, 2010; Hodges & Richardson, 1999).

In an observation study by Keefe (1998) LBP patients with longer pain history showed more guarding and bracing behaviour. Keefe defines guarded movement as "abnormally slow, stiff, interrupted, or rigid movement" and bracing as "stiff, pain-avoidant static position". Limited hip and spine mobility and compensatory movements in LBP patients and people with history of LBP have been described (Esola, McClure, Fitzgerald & Siegler, 1996; Shum, Crosbie, & Lee, 2005; 2007). The level of mobility has also been linked to the level of experienced pain (Koelman, Kwakkel & Wagenaar, 1996, as cited by Vlaeyen & Linton, 2000).

Electromyography studies have described decreased activation of deep trunk muscles, increased superficial muscle activation with stiffened body, and disturbances in lumbopelvic muscle coordination in people with LBP as well as in pain-free people

with previous history of LBP (Moseley, Nicholas & Hodges, 2004; Hodges and Richardson, 1999; MacDonald, Moseley & Hodges, 2010; Silfies, Bhattacharya, Biely, Smith & Giszter, 2010; Silfies, Mehta, Smith & Karduna, 2007).

Vollenbroek-Hutten, Schreurs, Rietman & Hermens (2010) found evidence for guarding movements during walking. People with LBP showed increased muscle activity during all phases of stride. Bath Assessment of Walking Inventory by Clarke and Eccleston (2009) consists of eight domains that are affected by chronic pain or indicate pain. These are ‘stride length’, ‘base of support’, ‘walking line’, ‘arm swing’, ‘turning’, ‘wall touch’, ‘rest’ and (use of) ‘aids’. People with LBP tended to have unequal stride length/limping, altered base of support (i.e. feet wider or narrower apart), and their arm swing was asymmetric or absent. They also tended to use more curved or meandering paths.

The mechanisms leading to altered movement in lower back pain patients have been reported to be partly mediated or moderated by psychological factors. Several studies have implicated pain-related fear as a key factor modulating the effects of lower back pain on movement (Leeuw, Hoube, Severeijns, Picavet, Schouten & Vlaeyen, 2007; Watson, Booker & Main, 1997; Thomas & France, 2007; Al-Obaidi, Nelson, Al-Awadhi & Al-Shuwaie, 2000). There is little evidence, however, that the “fear” probed by the questionnaires used is an independent factor rather than reflection of pain characteristics other than pain intensity: after all, two persons could very well have the same pain intensity but different response to physical activity, and there might even be no differences in their ability to perform the activity, only in the pain provoked by the activity. The questions or statements of the often used Fear Avoidance Beliefs Questionnaire (FABQ) (Waddell, Newton, Henderson, Somerwille & Main, 1993) include e.g. "Physical activity makes by pain worse", "I cannot do physical activities which (might) make my pain worse", and "My work makes or would make my pain

worse". It seems very difficult to justify why such questions would report on an independent “fear” rather than actual dependency of the pain intensity on activity and the resulting fear, and indeed this was not even attempted (Waddell, Newton, Henderson, Somerwille & Main, 1993). Accordingly, the results obtained using this questionnaire can hardly be taken as evidence for psychological factors independent of the nature of the current pain. Against this background the failure of interventions addressing fear of pain (Pincus, Smeets, Simmonds & Sullivan, 2010) appears unsurprising.

The catastrophizing response questionnaires would appear to be better measures of fear components, as they address the fear that the person is seriously ill and in danger of obtaining serious injury. Not surprisingly, such catastrophizing response is associated to more pronounced guarding and avoidance behaviour in movements (Al-Obaidi, Nelson, Al-Awadhi & Al-Shuwaie, 2000; Geisser, Haig, Wallbom & Wiggert, 2004; Vlayen & Linton, 2000).

Fear avoidance model suggests that fear of pain causes avoidance that leads to increased disability (for a review see Pincus, Smeets, Simmonds & Sullivan, 2010). A systematic review found little (if any) evidence for the prognostic value for fear assessed in early-stage pain, whereas some evidence for a correlation (though not causality) between level of function and fear in chronic pain exist (Pincus, Vogel, Burton, Santos & Field, 2006). Hence at present there appears to be no convincing evidence that the fear of pain measured represents a person's inherent maladaptive way to react to pain rather than a typical response to persistent pain with certain characteristics, or that therapeutic interventions addressing fear of pain could offer any treatment benefits. Nevertheless, the matter is not yet resolved, and although catastrophizing might not provide a therapeutic target, even the catastrophizing response scores (that concentrate on fears) appear to – at the very least – measure some

characteristic of pain or pain patients other than pain intensity, as these scores have been reported to correlate to increased lumbar muscle activity when walking (Van der Hulst, Vollenbroek-Hutten, Schreurs, Rietman & Hermens, 2010). Incidentally, in the same experiment (Van der Hulst et al., 2010) cognitive distraction lead to increased muscle relaxation, though it is difficult to conclude much about this, as cognitive distraction has also been extensively studied as a means of improving pain tolerance (see below).

Pain communication through vocal and facial expressions, posture, and movements

Pain has useful biological functions – as Amanda Williams describes it: "the function of pain is to demand attention and prioritise escape, recovery and healing" (Williams, 2002). For a social animal like humans communicating pain to others allows for the close kin and even community both helping and avoiding danger to themselves. This has likely provided a survival benefit, developing in extensive communication of pain (Williams, 2002). Humans express pain via vocalization, facial gestures and body posture and movement (Williams, 2002; Keefe, 1982; Keefe, 1998; Arif-Rahu, Fisher & Matsuda, 2011).

Limited amount of research exists on other than facial expression of pain. There is evidence, however, that people are able to identify emotions from posture and motions (Wallbott, 1998), and merely from watching a stylized figure, such as skeletal stick or point-light representation, of a moving human (Coulson, 2004; Atkinson, Dittrich, Gemmell & Young, 2004; Clarke, Bradshaw, Field, Hampson & Rose, 2005; Beck, Stevens & Bard, 2009; McDonnell, Jörg, McHugh, Newell & O'Sullivan, 2008). The role of expression of pain in motions and postures in communication is more difficult because (particularly in musculoskeletal pain) it may be necessary to adjust movements and postures to avoid increase in pain. Even if these adjustments were not intended to

communicate the existence of pain, others can conclude that the person has pain, and perhaps even its location. Hence, it is difficult to decipher to what extent the bodily expression of pain in LBP has significance in communicating the pain, as the changes in movement and posture that communicate pain are likely the same changes that allow avoiding pain. Some studies, however, have produced results that suggest that the pain behaviours may be classified in protective pain behaviours and communicative pain behaviours (Sullivan, Thibault, Savard, Catchlove, Kozey & Stanish, 2006). The protective pain behaviours include behaviours required to avoid increase in pain, such as guarding and bracing, and the communicative pain behaviours include facial expressions and vocal expressions such as words, grunts, and moans (Sullivan et al., 2006). Sullivan et al. (2006) found that the degree of protective pain behaviours correlated with the pain intensity and physical requirements of the task, but were unaffected by the focus on pain intensity (participants were asked to rate their pain during a task), whereas the degree of communicative pain behaviours strongly depended on the focus on pain intensity and were only slightly affected by the pain levels of the participants during the tasks. (Incidentally, this appears to suggest that the increase in protective pain behaviours observed in individuals with pain catastrophizing might not result from increased focus on pain.) Nevertheless, if bodily expression plays a role in communication of pain, one might expect that people in general also have behavioural representations for being in pain and that these could be activated by priming.

Priming is unconscious activation of behaviours by stimuli

Humans have behaviours and action tendencies that can be automatically and unintentionally triggered by environmental stimuli (primes), without involvement of conscious thought through incidental activation of trait concepts, cognitive representations, and stereotypes (Bargh, Chen & Burrows, 1996). This process is called

priming. In a classic study by Bargh, Chen & Burrows (1996) participants encountered subtle stimuli in the form of a scrambled sentence task containing words related to old age, such as grey, old, retired, wrinkle. As a result, the people who faced this puzzle had reduced walking speeds compared to those who faced a puzzle with neutral words, when the participants were secretly observed when they were leaving the room. Similar effects have since been reported in many studies (Bargh & Chartrand, 1999; Dijksterhuis & Bargh, 2001). The effects also extend to complex behaviour: Dijksterhuis & van Knippenberg (1998), for instance, found that priming the participants with stereotypes of professor/intelligent improved and priming with stereotypes of soccer hooligans/stupid degraded the participants' performance in answering Trivial Pursuit questions. These automatic activations may significantly reduce the cognitive load we constantly face by enabling quick and flexible transitions from one social situation to another upon encountering environmental stimuli.

The neurophysiological basis of priming-like effects have been implied to originate from the overlap between the perceptual and behavioural representations in brain: doing something, thinking about doing something, and seeing someone who is doing this thing largely activate the same regions or neuron populations in the premotor cortex of the brain (see Dijksterhuis & Bargh, 2001; Jeannerod, Arbib, Rizzolatti & Sakata, 1995). This principle that the same representation is shared by an action and perception is the common-coding hypothesis suggested by Prinz (1990; as cited by Dijksterhuis & Bargh, 2001). The processing in the neuronal networks of our brains is also highly interconnected, involving complex feedback signalling, and not simple, hierarchical, and sequential. It is not merely that something activates – for example – our happiness or amusement that then signals to lower level muscle activity that leads to smiling: a well-known example is that not only does seeing someone who smiles make us more likely to smile ourselves and tend to improve our mood (Hatfield, Cacioppo &

Rapson, 1993; Lundqvist, 1995), but also merely unconscious positioning of our facial muscles in the positions they occupy in smile improves our mood (Strack, Martin & Stepper, 1988; Soussignan, 2002), i.e. – to polemicize – not only being happy makes one smile but smiling makes one happy. Dijksterhuis & Bargh (2001) argue that the overlap of the perceptual and behavioural representations of an act leads to an inherent tendency to act as others do. They further argue that this adaptive perception evolved primarily to mediate functional responses to the environment.

There are several requirements for successful priming. Of course, the most important is that the trait- or concept-related behavioural representations to be activated exist (Bargh, Chen & Burrows, 1996). Another key requirement is that the situation should be relevant for the trait-related behaviour and the behaviour should not conflict with current goals of the person (Bargh, Chen & Burrows, 1996; Dijskterhuis & Bargh, 2001). For example, Strahan, Spencer & Zanna (2002) found that thirst-related primes increased the volume of drinks consumed only in individuals who were thirsty before priming. Additional modulating factors include (Dijskterhuis & Bargh, 2001) self-focused attention and disincentives. Self-focused attention tends to diminish the effects of priming (e.g. when the task is done in front of a mirror). If there is a significant disincentive against performing the priming-triggered action, priming will not work. For example in the experiment of Macrae and Johnston (1998) helpfulness-primed participants picked up significantly greater number of pens dropped by the experimenter than the control participants – unless the pens leaked ink: then the priming had no effect.

Another important requirement in priming is that the persons should be unaware that they are being primed for some purpose; otherwise the conscious processes are likely to take place and influence the behaviour (Dijksterhuis & Bargh, 2001). Wegner (1994) argued, however, that it requires effort to avoid the automatic behaviour and that,

therefore, when people are distracted, an ironic process is likely to happen: the activated concept tends to automatically start guiding the actions and the avoided action happens, even when the person only thinks about the concept in order to avoid the action. Accordingly, Dijskterhuis & Bargh (2001) argue that in order to control the influence of prime the person not only needs to be aware of the priming and but also needs to have enough motivation and cognitive capacity to control it.

Currently there is no evidence that priming people with pain-related concepts would change the way they move. If priming concepts such as elderly and intelligent individuals results in behaviour associated to these groups, it would appear likely that also priming with concept of being in pain would lead to behavioural alterations, in particular since expressing pain has been hypothesized to have an important evolutionary role for social animals such as humans.

Cognitive distraction can temporarily suppress pain by competing for resources

The finding that cognitive distraction can normalize changes in walking (Van der Hulst, Vollenbroek-Hutten, Schreurs, Rietman & Hermens, 2010) provides us with a potential experimental tool to counteract the effects of priming. This effect of cognitive distraction can be understood also in the context of the effect of cognitive distraction on pain. When pain is induced in experiments, cognitive distraction allows people to tolerate pain longer or decreases level of reported pain (Fernandez & Turk, 1989; Hodes, Howland, Lightfoot & Cleeland, 1990; Eccleston, 1994; 1995; Johnson & Petrie, 1997). The effect of cognitive distraction on pain has been studied on neurophysiological level as well. Functional MRI studies have given evidence that cognitive distraction leads to not only subjectively decreased pain scores, but also to decreased activation of pain-associated brain regions (Bantick, Wise, Ploghaus, Clare,

Smith & Tracey, 2002; Frankenstein, Richter, McIntyre & Rémy, 2001). This has fuelled interest in cognitive distraction as a coping mechanism in pain management.

The effects of distraction on experiencing pain have been explained by limited capacity models arguing that the load on the shared processing capacity between different pathways limits the capacity available for conscious experiencing of pain and decreases experienced pain (for reviews see Eccleston, 1995; Eccleston & Crombez, 1999; Johnson, 2005). Larger load on shared processing capacity, a more difficult distraction task, would thus be expected to provide stronger distraction, but several studies have failed to find support for this (Hodes, Howland, Lightfoot & Cleeland, 1990; McCaul, Monson & Maki, 1992; Eccleston & Crombez, 1999). Yet, more immersing (Malloy & Milling, 2010) or emotionally more engaging and pleasant (Stevens, Heise & Pfost, 1989) cognitive distractors are likely to give greater pain relief/tolerance (Johnson, 2005), which may imply that our ability to actively select the stimuli plays a role in the allocation of the resources of conscious thought. Motivational factors (such as the monetary rewards for good performance) and emotional factors (catastrophic thinking about the pain) have been found to modify the effect of cognitive distraction (Verhoeven et al., 2010), likely by affecting the level of immersion to the distractive activity. Those who are more afraid of pain and have catastrophic thinking about pain, are more aware of their body, more vigilant to pain, and do not immerse as deeply in the distractive activity (Crombez, Eccleston, Baeyens, & Eelen, 1998; Crombez et al., 1999; Roelofs, Peters, van der Zijden, & Vlaeyen, 2004; Eccleston, Crombez, Aldrich, & Stannard, 1997; Van Damme, Crombez, & Eccleston, 2004; Sullivan et al., 1998; all as cited by Johnson, 2005). Johnson and Petrie (1997) found that cognitive distraction enabled LBP participants tolerate exercise longer and do more repetitions compared to exercise without distraction. In addition, there was no increase of pain levels afterwards and those who were suffering from the higher levels of pain

had the highest increase in their ability to do the exercise. In a study by Goubert, Crombez, Eccleston & Devulder (2004), however, cognitive distraction had no effect on the pain levels during a lifting task and the LBP participants had more pain immediately after the task.

The issue of cognitive distraction-induced decrease in pain becomes even more complex if the effect of cognitive distraction is not studied using simple indicators describing tolerance, such as time the participants are able to withstand the cold pressor pain. Firstly, asking the participants about experience level of pain during the pain may draw their attention to pain and void the effects of distraction, and secondly, the distraction may affect how the painful experience is stored in memory. One of the two effects is likely to explain the result of Christenfeld (1997) who found that neither high nor low level of distraction produced significant decrease in self-reported pain levels when the assessment was done immediately after the cold pressor task, but that high level of distraction decreased self-reported pain levels if the participants were asked about their pain levels during the task 10 minutes after they had completed the task.

Cognitive distraction has variable effects on the way people move

In the present study we aim to employ cognitive distraction chiefly to dissipate the effects of priming, pain and fear of pain on the movement. Cognitive distraction on its own can affect movements of pain-free people, however. In an experiment by Barra, Bray, Sahni, Golding & Gesty (2006) the participants were asked to perform a balance task while attending to either a spatial or verbal task. In their study the spatial stroop task consisted of counting the congruent and incongruent stimuli when words “left” and “right” were delivered through headphones to either left or right ear. In the verbal stroop task the participants heard female and male names spoken by female or male voice, and they had to count the congruent and incongruent occurrences of the gender of the voice

and name. They discovered that the spatial task increased the rate of falls, but the verbal task did not. They also found that when the participants struggled maintain their balance, they abandoned the spatial task but continued performing the verbal task. Others have found that easy cognitive tasks make automatic motor tasks such as walking smoother, supposedly by focusing attention elsewhere, thus decreasing conscious interference and allowing automation take over (Huxhold, Li, Schmiedek & Lindenberger, 2006; Lövden, Schaefer, Pohlmeyer & Lindenberger, 2008), whereas more demanding cognitive tasks begin to have detrimental effects on motor performance, particularly in people with decreased cognitive capacity (Harley, Wilkie & Wann, 2009; Montero-Odasso, Bergman, Phillips, Wong, Sourial & Chertkow, 2009; Lindenberger, Marsiske & Baites, 2000; Schaefer, Huxhold & Lindenberger, 2006; Haggard, Cockburn, Cock, Fordham & Wade, 2000; van Iersel, Kessels, Bloem, Verbeek & Rikkert, 2008). Likewise, it seems that cognitive tasks more easily interfere in situations where transitions or changes in automatic motion are required (Daniels & Newell, 2003). Hence, it seems that cognitive tasks that are easy relative to the cognitive capacity of a person do not interfere with easy motor tasks, but increasing difficulty in either may result in slower motor task performance.

Summary and hypothesis: the effects of pain priming and cognitive distraction on the kinematics of people who have suffered from back pain

The previous work on the kinematics of back pain patients has demonstrated more guarded movements, increased bracing, and altered muscle activation in the back (Van der Hulst et al., 2010; Keefe, 1998; Esola, McClure, Fitzgerald & Siegler, 1996; MacDonald, Moseley & Hodges, 2010; Hodges & Richardson, 1999). Clarke and Eccleston (2009) noted that in walking stride length, base of support, walking line, and arm swing were affected by pain. Others have reported changes in maximum walking

speed, though the preferred walking speed appears only weakly correlated to LBP (Simmonds, M. J & Claveau, Y., 1997; Simmonds et al., 1998). The effects of back pain on movement persist long after the back pain is gone (Leeuw, Hoube, Severeijns, Picavet, Schouten & Vlaeyen, 2007; Watson, Booker & Main, 1997; Thomas & France, 2007; Al-Obaidi, Nelson, Al-Awadhi & Al-Shuwaie, 2000; MacDonald, Moseley & Hodges, 2010; Hodges & Richardson, 1999). Priming the participants with concepts related to pain and the participants remembering their pain should activate the regions of brain related to perception and experience of pain, and this would be expected to activate also the regions corresponding to the expression of pain in movements. The cognitive distraction is expected to make the participants move in the manner that is more automatic, i.e. in a manner that requires less concentration or conscious thought. This is because cognitive distraction leaves less capacity available for conscious modification of movements. In back pain sufferers the abnormally activated muscles of the back have been reported to become more relaxed under cognitive distraction (Van der Hulst er al., 2010).

Therefore we hypothesized that 1.) by priming the participants with previous experience of back pain with pain-related concepts we could induce in their walking kinematics changes similar to those observed in patients with current back pain, and that 2.) cognitive distraction should tend to lead to more normal walking behaviour. We selected a cognitive task that did not require spatial information processing and, hence, based on literature (Huxhold, Li, Schmiedek & Lindenberger, 2006; Lövden, Schaefer, Pohlmeyer & Lindenberger, 2008), is not expected to have large effects on kinematics in itself.

Method

Participants

There were 23 participants in the study, nine males and fourteen females, aged 18–65 years. They were either UCL students or staff members and they were recruited by sending an email to UCL-wide email list (for the email see Appendix 1). The original email invites everyone with experience of episodes of pain, but the ones with history of low back pain episodes were chosen from those willing to participate. The exclusion criteria were 1.) a current pain condition, 2.) a physiological or neurological condition that could affect the performance. However, despite the screening, some of the participants reported experiencing pain during the experiment as assessed by Visual Analogue Scale (VAS) (Price, McGrath, Rafii & Buckingham, 1983). The data of two participants was discarded because they had guessed the purpose of the experiment.

Materials

Various questionnaires (see below) including McGill Pain Questionnaire (Melzack, 1975; Appendix 2), Brief Pain Inventory (Cleeland & Ryan, 1994; Appendix 2), visual analogue scale of pain (Price, McGrath, Rafii & Buckingham, 1983; Appendix 3), Positive Affect Negative Affect Scales, PANAS (Watson, Clark & Tellegren, 1988; Appendix 4–5), and International Physical Activity Questionnaire, IPAQ, (Craig et al., 2003; Appendix 6) were used at different points of the study (see Fig. 1).

Pain priming and pain level monitoring. The purpose was to activate the participants' recollections related to their pain and hence prime them with the concepts of pain. To achieve this, the participants were briefly interviewed about their pain episode, and they were asked to answer a questionnaire focusing on the previous episode(s) of pain (see Appendix 2). The questionnaire was constructed from McGill Pain Questionnaire (Melzack, 1975) and Brief Pain Inventory (Cleeland & Ryan, 1994).

The participants' answers to questions 1–2 were collected by interviewing. Question 7, visual analogue scale of pain (Price, McGrath, Rafii & Buckingham, 1983), was included to monitor the participant's pain level in the experimental situation, because existing pain and drawing attention to it could override any priming effects. The participants' pain level was also assessed by VAS after the pain priming condition and after the cognitive distraction condition (see Appendix 3 for VAS).

Mood/emotion monitoring. Since mood and emotions can affect movement and posture, the participants' affect was monitored by asking the patients to fill in Positive Affect Negative Affect Scales, PANAS (Watson, Clark & Tellegren, 1988) three times during the experiment: first in the beginning of the experiment (Appendix 4), after the pain priming condition, and after the cognitive induction condition (see Appendix 5).

Controlling level of physical activity. Since the level of physical activity could affect their posture and movement, the level of participants' physical activity was controlled for by using a short version of International Physical Activity Questionnaire, IPAQ, (Craig et al., 2003) (see Appendix 6).

Physical exercises. The participants performed sequentially five exercises or "everyday tasks" selected by a physiotherapist. In this study only walking was analyzed, rest of the data was used for other purposes. The tasks were:

1.) Standing on one leg for five seconds. Both sides were done twice. Order: left, right, left, right.
2.) From stand-to-sit and sit-to-stand. Three times. At their own pace.
3.) Walking five meters ahead and back. At their own pace.
4.) Holding a 3.5 kg backpack for ten seconds. Grip from sides. Arms straight.
5.) Carrying a 7 kg trolley for five meters. Grip from the top handle. Superior hand.

Cognitive distraction. The goal was to choose a cognitive distraction method that would interfere with pain sensation, but not affect physical exercises. Because the

exercises require vision, posture- and movement-related cognitive capacity, an auditory task was selected. Originally Paced Auditive Serial Addition Task (PASAT) was selected because it has successfully inhibited pain as measured both by pain-related autonomic activity and by subjective measures (Terkelsen, Andersen, Mølgaard, Hansen & Jensen, 2004). In PASAT the participant listens to random numbers (e.g. between 1–9) played at regular intervals (e.g. 30 numbers/min) and he has to speak aloud the sum of the previous two digits in the series. However, in pilot tests PASAT caused too much cognitive load: the participants failed to sum up the numbers fast and correctly enough and struggled to perform the exercises simultaneously. Thus a modified version of task by Johnson and Petrie (1997) was adopted. In the original task the participants had to listen to and repeat nouns while paying attention to a screen on which a pair of words were presented. If the words on the screen were the same they heard, they were instructed not to repeat them. The goal was to keep the participants' attention on the task. To utilize the same principle, in this study the participants were played an audio track of random numbers (1–9); the task was to shadow the numbers, repeating aloud only even, but not odd numbers. The random numbers were pronounced by a software generated female voice and played from loudspeakers at 30 words/minute.

Apparatus

The movements and posture were recorded by using commercially available Animazoo IGS190 gyroscopic motion capture suit. Instead of a lycra suit, the gyros (motion sensors) in our version were attached using velcro straps. The experiment was video-recorded. The random numbers for cognitive distraction were generated by Excel random number generator and copy-pasted to Natural Reader for conversion into an audio file. The audio file was then imported to Free Audio Editor, and 1600 ms of

silence was added after each word. The audio file was played by using iTunes and PC World Essentials 2.0 Speaker loudspeakers.

The data analysis was done using a full version of Matlab 2010a (7.10.0.499) running on 64-bit Windows 7 OS on a computer equipped with 8 GB of RAM and a X3430 2.4 GHz Xeon processor. The Matlab script written to analyze the files utilized the MATLAB Motion Capture and NDLUTIL toolboxes by Prof. Neil Lawrence (2010).

Design

There were three conditions: 1) Control condition, 2) Pain priming, and 3) Cognitive distraction. A within-participants design was used. Control condition was always done first. Its purpose was to act as a baseline condition and to allow the participants to familiarize themselves with the setup. The Pain priming and Cognitive distraction conditions were counterbalanced for the participants (see Figure 1).

The independent variable was the activity of the participant during or immediately before the movement: i.e. nothing in the control condition, pain priming before the priming condition, and the cognitive task during cognitive distraction condition. The dependent variables were numeric characteristics of posture and movement (stride frequency and length, the width for the base of support, linearity of walking, and left–right asymmetry variable) as well as data collected by questionnaires.

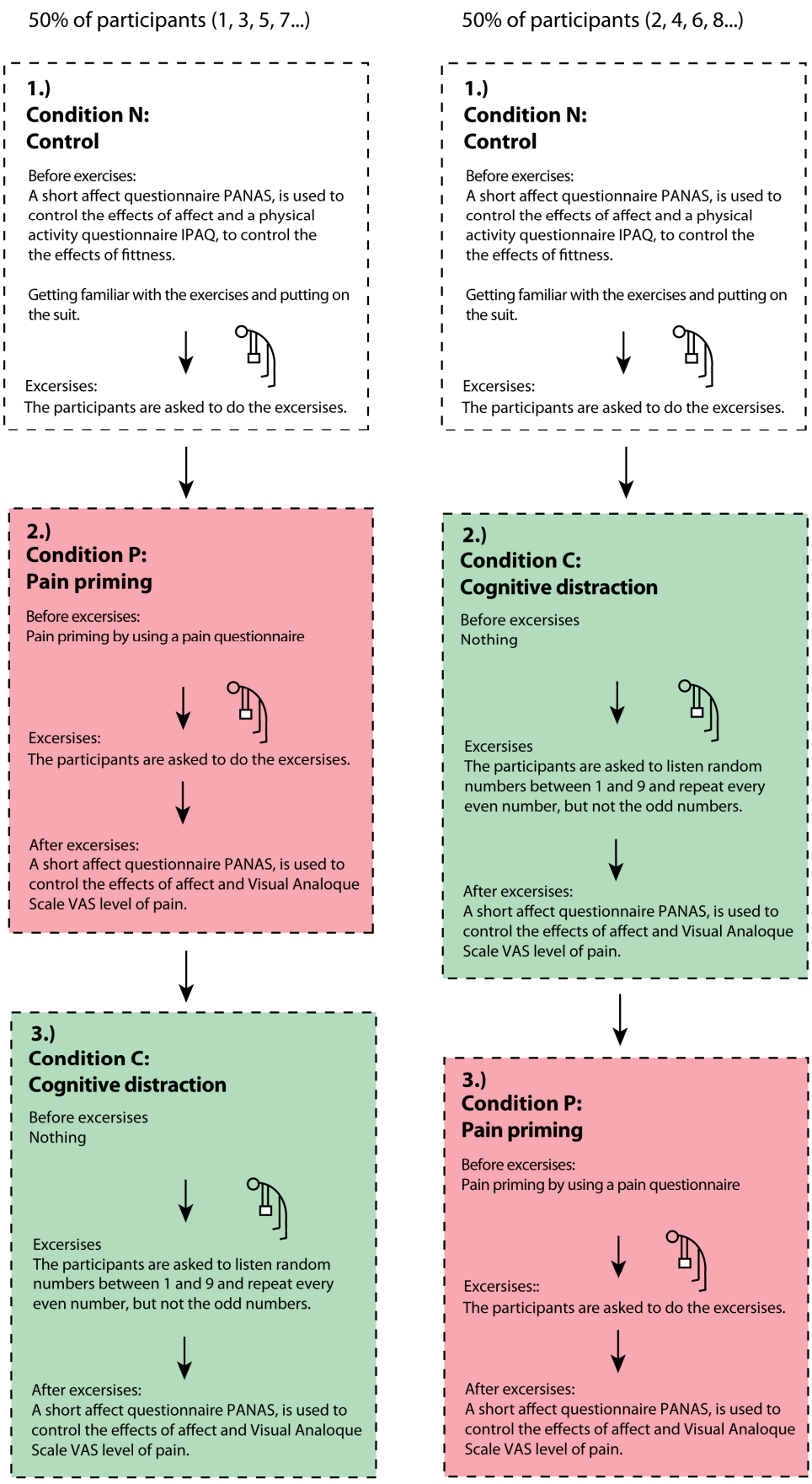

Figure 1. The experimental conditions

Procedure

The participants were tested individually in UCL premises. The test room was selected so as to avoid metal structures that result in inhomogeneous magnetic fields and cause artefacts in recordings. In the beginning of the experiment the participants were greeted, asked to sit down, introduced to the motion capture suit, the technique, the exercises, and told that they were to fill several questionnaires during the experiment. The participants first filled up the first mood questionnaire (PANAS) and the physical activity questionnaire (IPAQ). Then the motion capture suit was put on and the system was configured. For the configuration the participant had to stand still for approximately two minutes while the experimenter checked that the gyros were recording correctly. To complete the calibration procedure, the participant was asked to face north and the system was locked to Earth's magnetic field (called also "take-the-north" procedure). Sometimes the north had to be taken several times, likely because of inhomogeneous magnetic fields in the room.

The exercises were explained to the participants and they were given some time to try and memorise them. When the participant was ready, the experiment started. The participants did the exercises continuously at their own pace, except when standing on one leg or holding the backpack; in these tasks the experimenter indicated when the time was reached by waving a hand. In the case the participant forgot what to do next, the experimenter mimicked the movement silently. The participant performance was recorded in every condition by using a digital video recorder and Animazoo motion capture technology. After the control condition half of the participants were assigned to the pain priming condition followed by cognitive distraction condition (participants 1, 3, 5, 7, … 23) and another half to cognitive distraction condition followed by pain priming condition (participants 2, 4, 6, 8, … 22) (see Appendix 7 for participant information).

In pain priming condition participants were primed by using the pain questionnaire. The answers to the first two questions were collected by interviewing; this served as an introduction and the participants answered the rest of the questions in writing. Then the participants were asked to perform the exercises and the performance was recorded. In the end of the pain condition the participants were asked to fill in VAS and PANAS for recording the pain level and the affect they had while performing the exercises.

In cognitive distraction condition the participants were asked to perform the same set of exercises again, but they had to listen to random numbers between one and nine at the same time and repeat every even number (two, four, six, eight) they heard, but not the odd numbers (one, three, five, seven, nine). In the end of the condition the participants were asked to fill in VAS and PANAS for recording the pain level and the affect they had while performing the exercises.

In the end of the experiment the participants were asked what they thought was measured in the experiment and why. The participants were given a debriefing session in which they were allowed to ask questions. They could also try to move a bit in the suit and see their avatar moving. Then the suit was taken off, the participants were thanked and given two boxes of chocolate.

Results

There were 18 sensors (Figure 2) recording angle of rotation in three orthogonal directions, each 60 frames per second. Hip gyro also recorded X, Y and Z coordinates and served as the root (or reference) body part. The XYZ coordinates of the other body parts can be calculated using the hip XYZ coordinates and the data on joint angles and the lengths of body segments (such as spine, thigh, leg, foot); the latter were saved during the initial calibration of the motion capture system. Because of limited time available for data analysis, this experiment focused on the variables extracted from the data related to walking, other data will be analyzed later by others.

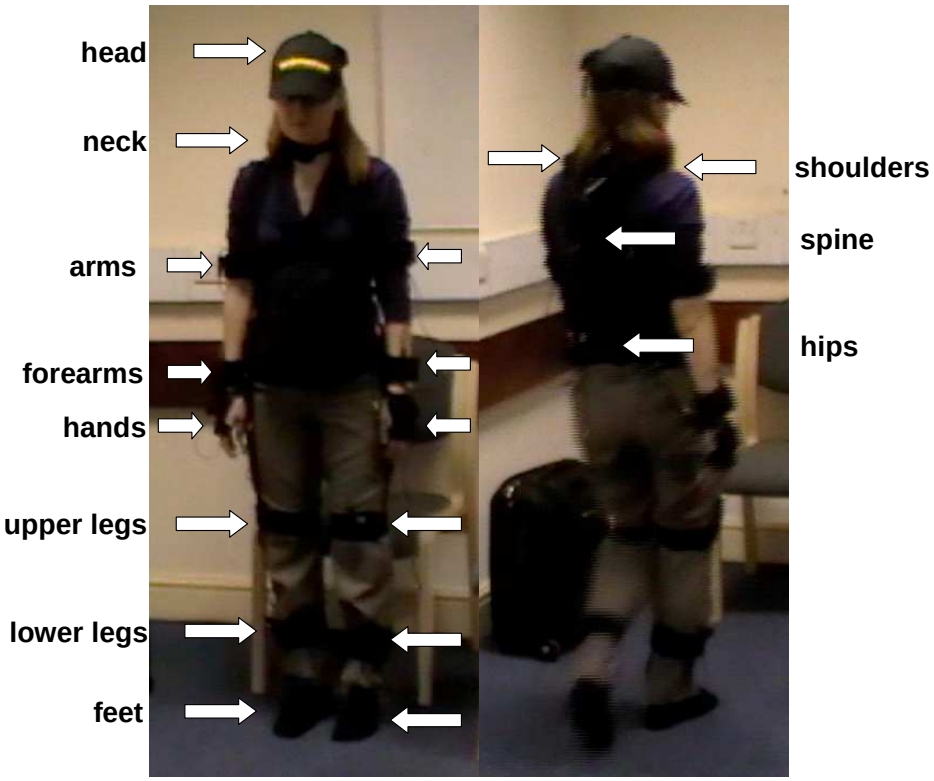

Figure 2. The sensor placement. The positions of the 18 sensors are shown with arrows.

The motion capture data was analyzed using a custom-made graphical Matlab user interface (see Figure 3 for a screenshot of GUI) utilizing functions by Neil Lawrence (2010) for importing and converting the motion capture .bvh files as well as

self-written functions for data analysis. Briefly, the motion capture data was used to plot a stick character in Matlab (see Figure 3), and the data frames containing walking were extracted from the rest of the data by plotting the character movement frame-by-frame and choosing the correct set of frames for analysis. Likely because of inhomogenous magnetic fields in the measurement rooms many recordings had artefactual sliding in spatial (i.e. hip XYZ) coordinates. Before calculation of certain variables such as stride length, the artefactual sliding needed removing. Two subsequent corrections were applied, both aiming to identify the supporting foot on ground and using the information that supporting foot is not really moving. The two subsequent corrections gave very good results as evaluated by the absence of visible sliding upon visual evaluation of the stick character movies. For details of the calculation of the corrections and for examples of original and corrected movies see Appendix 8. After these corrections the key variables were extracted from the data.

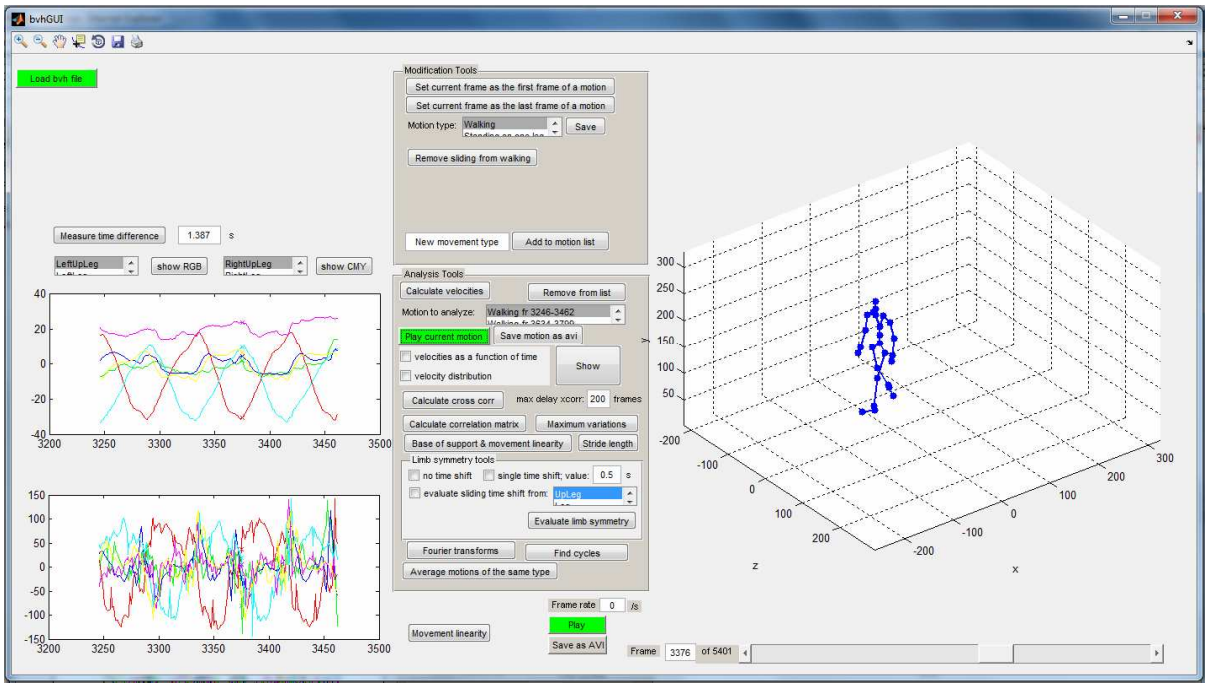

Figure 3. Screenshot of the Matlab GUI used in data analysis

Key-variable extraction

The key variables extracted to analyse the walking patterns were stride frequency (stride cycles per second), width for the base of support (the mean distance between feet in the direction of straight angles against the walking direction), stride length, a linearity characteristic for walking (actual path distance divided by linear path distance), and finally a left–right asymmetry variable calculated (as described later) from left–right differences in descriptive sensor statistics. The rationale for choosing these variables is that Clarke and Eccleston (2009) reported that pain increased deviation from linearity during walking, affected the width of the base of support, and increased left–right asymmetry in both upper limb and lower limb movements, and Keefe reported that people in pain show abnormally slow movements.

The stride frequency was calculated from the period obtained by averaging the first non-zero peak positions of the autocorrelation curves for the lower limb sensor data. The autocorrelation correlograms were calculated using standard Matlab xcorr function and the peak positions were extracted using function PeakFinder by Nate Yoder (2011). In panel A of Figure 4 examples of original data (one the three rotations (X') for both right and left upper leg) are shown, as well as an imaginary curve (blue dotted line) to demonstrate the principle of the calculation of autocorrelation, i.e. a curve is considered to be shifted with respect to itself by a time Δt, and then autocorrelation value is calculated. This results in autocorrelation curves (Figure 4 B) that show peaks at such values of Δt where the shape of original data repeats. The Δt values of first peaks (excluding the one at $\Delta t=0$) were taken as the cycle time.

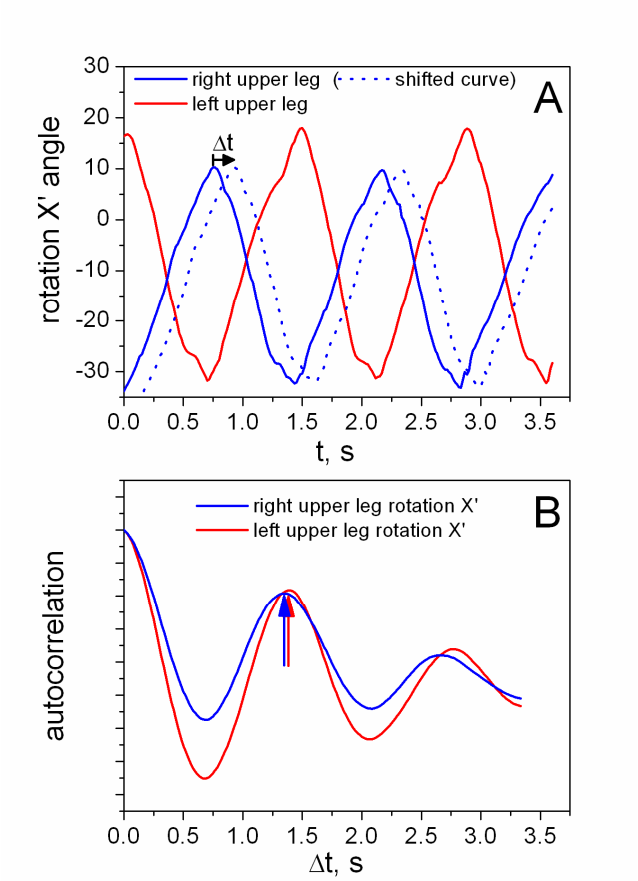

Figure 4. Examples of the angular data and computed autocorrelation curves. In panel A examples of actual sensor data for the upper leg sensors (continuous lines) as well as a shifted curve (dotted line). The autocorrelation functions (panel B) peak at the time-shift values where the shifted curve follows the original curve.

The width for the base of support was calculated as the mean distance in the direction of movement normal between left and right foot. To obtain this value, the movement vector was calculated from the hip XY coordinates of the previous and next data points, the vector connecting the feet was calculated from feet XY coordinates, and standard vector calculus and Pythagorean theorem were used to compute the projected distances between feet both in the direction along the movement and in the normal direction, the latter taken as the base width (Figure 5).

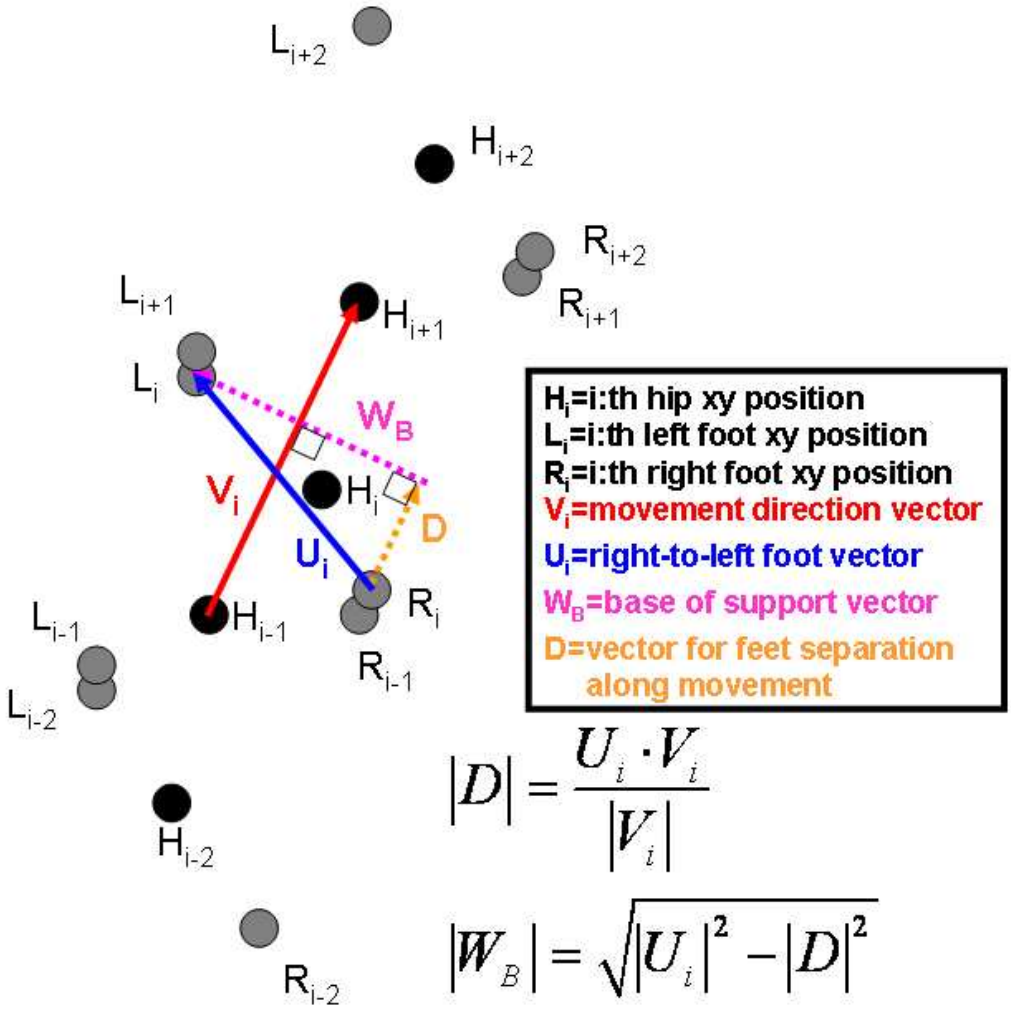

Figure 5. The calculation of the width for the base of support. The width for the base of support was calculated as the average of instantaneous values. At each time point i the instantaneous base width at a straight angle against the instantaneous direction of the movement was computed as shown in the figure.

The stride length for each foot was calculated simply as the distance in the floor (=XY) plane between the positions occupied by the foot in two subsequent positions where the foot was the foot with the lowest vertical (Z) coordinate (see Figure 6); the upper panel shows the cumulative distance travelled by the right and left feet as a function of time, and the lower panel shows the vertical position of the right and left feet as a function of time. Note that the cumulative distance difference in Figure 6 is not the stride length, but instead the stride length was the minimum distance between the

foot positions at the time points indicated by dotted lines. All the stride lengths were manually checked to remove steps broken into small pieces as for some participants the time points where the supporting foot on ground changed, either the foot vertical (Z) coordinate data contained inaccuracies or the real foot positions were temporarily such that the supporting foot appeared to be higher than the moving foot.

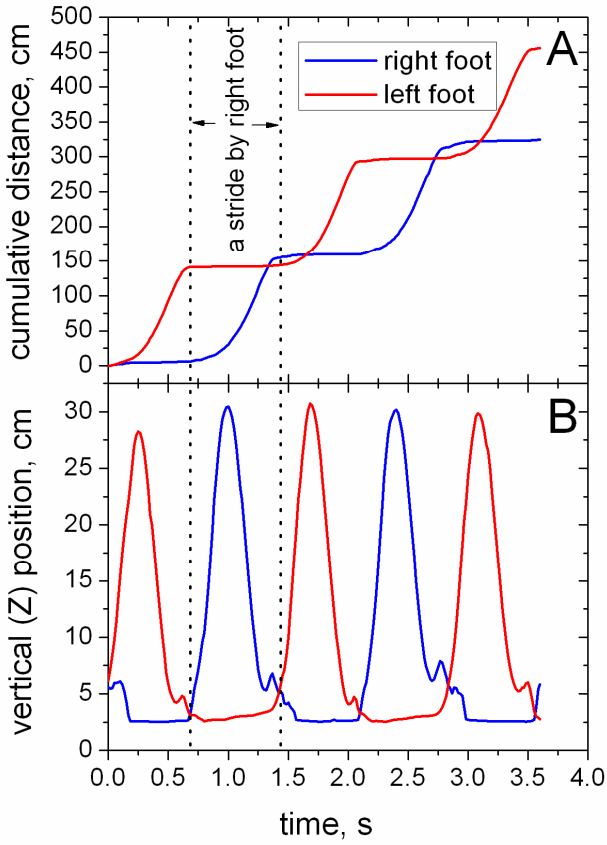

Figure 6. The movement and vertical positions of feet as a function of time. In upper panel (A) the cumulative distances travelled by the feet as a function of time are shown. In the lower panel (B) the vertical (Z) positions of the feet as a function of time are shown. The vertical dotted lines show the beginning and end for a stride for the right foot, i.e. the times when it stops being the lowest foot and again becomes the lowest foot. Note that the difference in cumulative distance (panel A) between these times is not the stride length, but instead the stride length is the distance between the corresponding right foot positions.

To estimate the linearity of walking, the XY coordinate pairs occupied by the root body part (centre point between the hips) during walking were line fitted (to Y=a+bX) using the standard least squares method. The simple descriptor extracted to describe linearity was the ratio of the actual path length to the fitted, linear path length (see Fig. 7).

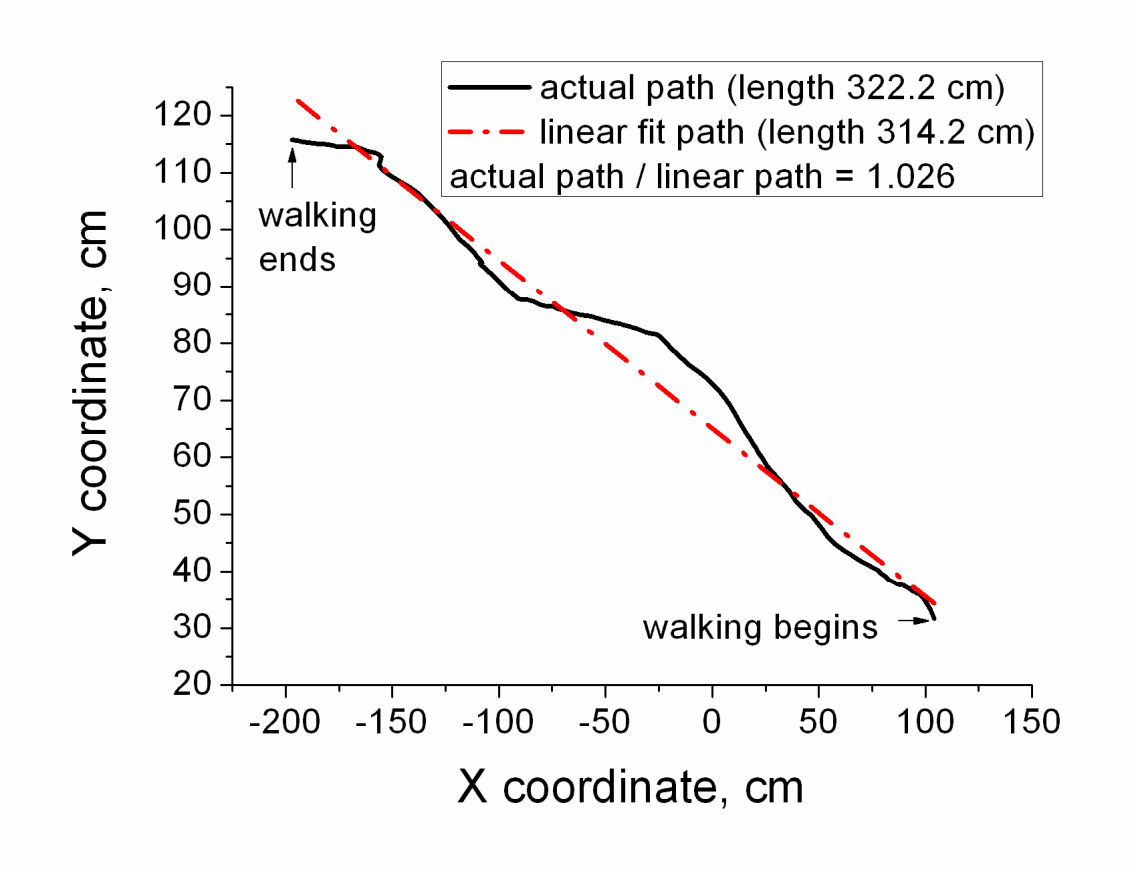

Figure 7. An example of the actual path and the linear path. The XY coordinates are in the floor plane, i.e. the figure shows the walking path of the participant from above.

The descriptive statistics of the data were calculated for the data of all the sensors (mean angle, standard deviation, amplitude, mean angular velocity, standard deviation of angular velocity, and amplitude of angular velocity), and the left–right differences from this data were also calculated (for seven sensor locations reporting 21 angles). Since the number of sensors is large, there are numerous variables to compare. In fact there would be N=126 left–right comparisons to make. In order to compare multiple

variables by (any) *t* tests using the overall significance level selected at 0.05, the value of α for the individual tests would have to be adjusted for multiple tests according to $\alpha=1 - 0.95^{1/N}$ where N is the number of tests performed. A problem with data that has numerous variables is that even for true effects the significance may be lost in the large numbers of tests performed: in our case N=126 and $\alpha\approx0.0004$ when overall significance level of 0.05 would be used. Therefore for the analysis of left–right asymmetry the left–right differences were collapsed into a single parameter for further testing.

In the collapsing of the data it becomes a problem to choose from amongst the the various differences (many of which may merely be noise) in descriptive statistics the left–right differences actually reflecting the left–right asymmetry during walking. Each condition contained two stretches of walking (forth and back) for each participant. To choose the parameters to be collapsed into a single asymmetry variable the absolute left–right differences for each stretch of walking were calculated and divided by the mean of the values for the left and right side for that person during that stretch of walking, i.e.

$$d_{i,j,k} = \frac{\left|P_{i,j,k,L} - P_{i,j,k,R}\right|}{\frac{1}{2}\left(P_{i,j,k,L} + P_{i,j,k,R}\right)},$$

where d is the difference in question, P is the property value in question (such as foot rotation 1 amplitude), and i, j, and k indicate the participant number, the condition, and the walking stretch (forth=1 or back=2) within the condition, and subscripts L and R indicate the left and right side). Then each of these left–right differences ($d_{i,j,k}$) for a given property and sensor for the second stretch of walking (=back, $d_{i,j,2}$) were plotted against the left–right differences for the first stretch of walking (=forth, $d_{i,j,1}$) within the same condition for the same participant. After this, the Pearson correlation coefficient for the data for all the participants and all the conditions was calculated. The rationale was that left–right asymmetry in truth reflecting the way the participants walk should

remain the same after the participants turn and walk the same stretch back, i.e. the left–right asymmetry values should be nearly equal and hence the correlation coefficient should be close to 1, whereas for noise the correlation coefficient should be close to 0. All the correlation coefficients are shown in Appendix 9. Based on arbitrary scoring scheme (where each correlation coefficient r was given the score 10^r and the sensors with total score >30 were included and then the properties with score >25 for the included sensors were included), data for upper leg rotation X', foot rotation X', shoulder rotation Z', arm rotation X', and forearm rotation X' and the variables position (i.e. rotation) amplitude, position standard deviation, and angular velocity standard deviation were selected for the calculation of the collapsed asymmetry variable (see Table 1 for the forth–back Pearson correlation coefficients of the selected sensors and properties).

Table 1.

Correlation coefficients for left–right asymmetry descriptors between two stretches of walking within conditions: selected sensors and properties

	ANGULAR POSITION		**ANGULAR VELOCITY**
	A	**std**	**std**
UpLeg rot1	0.97	0.95	0.91
Foot rot1	0.71	0.80	0.61
Shoulder rot3	0.55	0.51	0.86
Arm rot1	0.71	0.72	0.78
Forearm rot1	0.53	0.60	0.67

Each of the selected variables was normalized by subtracting its mean and by dividing with its standard deviation.

$$D_{i,j,k} = \frac{\left(d_{i,j,k} - \overline{d_{i,j,k}}\right)}{\sigma_{d_{i,j,k}}},$$

where the average and standard deviation are calculated over all the participants, conditions and walking stretches. The collapsed asymmetry variable Δ was calculated as a correlation coefficient-weighted sum of the included normalized values, i.e.

$$\Delta_{i,j,k} = \sum_{m=1}^{M}\sum_{n=1}^{N} r_{m,n} D_{m,n,i,j,k} \ ,$$

where *m* is the sensor (M=5, see Table 1), *n* is the property (N=3, see Table 1), and i, j, and k indicate the participant, condition, and walking stretch. These values were then used in later testing.

The means and standard deviations for all the key variables in different conditions as well as for the differences between conditions are shown in Table 2. The affect scores and pain levels in different conditions are shown in Table 3.

Table 2.

Key walking characteristics and between-condition differences for them.

	Control	**Cognitive distraction**	**Pain priming**
variable	mean±std	mean±std	mean±std
stride frequency, cycles/s	0.83±0.08	0.82±0.08	0.84±0.08
width for the base of support, cm	15.7±5.1	15.7±4.2	15.7±5.4
stride length, cm	124±14	120±15	122±17
actual path / linear path	1.093±0.071	1.125±0.084	1.147±0.092
asymmetry variable	0.78±4.50	-0.96±4.13	0.69±6.18
	Pain-Cognitive	**Pain-Control**	**Cognitive-Control**
differences	mean±std	mean±std	mean±std
stride frequency, cycles/s	0.02±0.07	0.01±0.03	-0.01±0.07
width for the base of support, cm	0.02±4.43	0.04±5.66	0.02±3.54
stride length, cm	1.6±6.3	-2.2±9.2	-3.8±8.5
actual path / linear path	0.020±0.074	0.050±0.105	0.030±0.077
asymmetry variable	1.65±5.43	-0.09±4.36	-1.74±5.32

Table 3.

Affect scores (PANAS) and pain levels (VAS) in different conditions

	Control	**Cognitive distraction**	**Pain priming**
variable	mean±std	mean±std	mean±std
positive affect score	27.0±9.3	29.2±8.2	26.3±9.0
negative affect score	12.4±3.8	12.3±3.6	11.5±2.3
	After cognitive distraction	**During pain priming**	**After pain priming condition**
VAS	1.02±1.29	0.80±0.68	1.00±1.05

Statistical testing for differences between conditions

The asymmetry parameter, stride length, stride frequency, width for the base of support, and actual/linear linear path (Table 2) were included in later analysis in addition to VAS and PANAS scores (Table 3). A repeated-measures (i.e. within-participants) two-way ANOVA in analysis was used in SPSS version 15.0.1. At the significance level α=0.05 the main effect of the condition was not significant and the interaction of condition*(order or conditions) was not significant for any of the walking characteristics, VAS, or PANAS scores. Accordingly, none of the differences between cognitive distraction and pain priming conditions were significant (at α=0.05) by using paired-sample t-tests.

Correlation between changes in affects scores or VAS score and walking characteristics between conditions

It was also evaluated if the differences for individual participants in walking characteristics between pain priming and cognitive distraction conditions correlated with the differences in VAS or PANAS scores. No significant correlation was found, which most likely derives from the lack of significant differences between conditions

for any participants in these scores and characteristics rather than from a real lack of effect of changes in pain and emotions on these walking parameters.

Estimation of test–retest reliability for walking characteristics

The lack of effects and correlations raises questions of the reliability of the computed walking characteristics. In each condition the walking consisted of two stretches, as the participants first walked the other way, turned, and then walked back. The test–retest correlations between these two stretches were calculated. These correlations are not true test–retest correlation values, as they are not results from two independent tests for the participant, but were measured within the same test. They do provide upper limit estimates for test–retest reliability, however, though it should be noted that longer walking distances would probably significantly improve the reliability of obtained values – after all, because the participants began turning at the end of the walking, the actual straight walking distance was less than four metres for many participants and contained only a few pairs of strides. Since the condition had no significant effect on the walking characteristics, one can assume that if any effect exists, it will be small or be apparent only in a minority of participants. On the other hand, if the parameters for walking characteristics were good descriptors of how a person walks, one would assume that the variation in parameter values between people should be much larger than the variation in parameter values between different conditions for a same person. Accordingly, there should be high correlation between the values for the participants in one condition to those for the same participants in another condition. The correlation coefficients for the data of control vs. cognitive distraction, control vs. pain priming, and cognitive distraction vs. pain priming conditions were calculated. The obtained correlations cannot be taken as actual indicators of test–retest reliability since the values were measured in different conditions, and if the condition affects these characteristics

for some participants though not sufficiently to reach statistical significance in our sample, the correlation will be decreased. These correlations thus provide lower limit estimates for test–retest reliability. Considering all of the correlations (Table 4), the stride frequency, stride length, and base of support nevertheless appeared to be relatively good, reliable characteristics of participants' walking, whereas left–right asymmetry variable and walking linearity characteristic had less reproducibility. The poor reproducibility of the walking linearity characteristic was expected, despite the good reproducibility reported by Clarke and Eccleston (2009), since in their study the participants walked for two minutes and in our experiment the participants only walked for a few seconds or a few pair of strides, and clearly the meandering about the path or the curving of the path will not be significant within these few steps. Indeed, the reason that actual/linear path distance shows any reproducibility may derive from the fact that it is also affected by swaying of the hips – that within these short stretches of walking may have equally or more important contribution than the actual meandering of the path.

Table 4.

Upper and lower limit estimates of test–retest reliability

walking characteristic	**correlation for forth–back walking within conditions**	**correlation between conditions**
stride frequency	0.92	0.73[1]
stride lenght	0.93	0.89
base of support	0.75	0.56[2]
actual/linear distance	0.72	0.43
asymmetry variable	0.81[3]	0.48

[1]One participant had much lower frequency in cognitive distraction condition than in control or pain priming conditions, and one had higher; without the cognitive distraction condition data of these two participants the correlation would reach 0.86.

[2]A single participant (first of the participants in footnote 1) had much wider base of support in pain priming condition; without the pain priming condition data of this participant the correlation would reach 0.75.

[3]Note that the values for the asymmetry variable were selected so as to make this within-conditions correlation high.

Correlations between walking characteristics and participant characteristics

Since there appeared to be no differences between conditions for the participants but there were differences between participants in each condition, the data collected for each of the participants was averaged over the conditions. Then the correlations between the averaged variables as well as other variables (such as age, height, weight, and the average pain levels they had suffered during their pain episode) associated to the participants were computed. Some variables that appeared to provide no significant correlation (see Appendix 10) were omitted from the correlation analysis. The analysis showed some unsurprising correlations, such as the correlations between sex, height, and weight, and general current pain levels and pain levels experienced during experiment (Table 5). Some surprising correlations were also revealed, such as the positive correlations between stride frequency and weight and between stride frequency and age; it is doubtful that these correlations would extend beyond our participant population, as they seem to suggest that heavier and older people walk with greater stride frequency. Base of support also appeared to correlate with sex, but no significant independent correlation remained when partial correlation was computed, taking into account the mutual correlations between sex, height, and weight. Although the pain levels reported during the experiment were in general very low, marginal negative correlation (-0.54) between stride lenght and VAS score was observed, and marginal positive correlation (0.51) between the width for the base of support and VAS score, in keeping with the effects of pain reported in literature. Although the correlation is very weak, the agreement with earlier reports implies that it could be real rather than arising from random variation.

Table 5

Correlation between different variables in the participant population

		Sex	Age	Height	Weight	Average pain during episode	Current pain score	Walking inter-ference score	IPAQ	VAS during experim ent	Stride frequency	Asymm. score	Stride length	Base of support	Actual distance per linear distance
Sex (female=0, male=1)	Pearson Correlation	1	.182	**.608 (**)**	**.745 (**)**	-.198	-.160	.186	.421	.115	.246	-.069	.406	**.496 (*)**	.098
	Sig. (2-tailed)		.442	.004	.000	.403	.501	.433	.072	.639	.296	.772	.076	.026	.681
	N	20	20	20	19	20	20	20	19	19	20	20	20	20	20
Age	Pearson Correlation	.182	1	-.340	.255	-.110	.036	.083	-.415	-.232	**.533 (*)**	-.392	.005	-.029	-.143
	Sig. (2-tailed)	.442		.142	.293	.644	.881	.728	.077	.338	.015	.087	.982	.903	.547
	N	20	20	20	19	20	20	20	19	19	20	20	20	20	20
Height	Pearson Correlation	**.608 (**)**	-.340	1	**.547 (*)**	-.191	-.352	.107	.449	.129	.127	.011	.366	.219	-.053
	Sig. (2-tailed)	.004	.142		.015	.419	.129	.653	.054	.598	.594	.964	.113	.355	.824
	N	20	20	20	19	20	20	20	19	19	20	20	20	20	20
Weight	Pearson Correlation	**.745 (**)**	.255	**.547 (*)**	1	.072	-.103	.313	.370	.068	**.668 (**)**	-.099	.246	.450	.005
	Sig. (2-tailed)	.000	.293	.015		.768	.676	.192	.131	.789	.002	.685	.309	.053	.983
	N	19	19	19	19	19	19	19	18	18	19	19	19	19	19
Average pain during episode	Pearson Correlation	-.198	-.110	-.191	.072	1	-.087	**.452 (*)**	-.088	.056	-.002	.325	-.352	.103	.389
	Sig. (2-tailed)	.403	.644	.419	.768		.715	.046	.721	.820	.993	.163	.128	.664	.090
	N	20	20	20	19	20	20	20	19	19	20	20	20	20	20
Current pain score	Pearson Correlation	-.160	.036	-.352	-.103	-.087	1	.094	.191	**.567 (*)**	-.022	-.198	-.283	.332	-.172
	Sig. (2-tailed)	.501	.881	.129	.676	.715		.693	.434	.011	.928	.402	.227	.153	.468
	N	20	20	20	19	20	20	20	19	19	20	20	20	20	20
Walking inter-ference score	Pearson Correlation	.186	.083	.107	.313	**.452 (*)**	.094	1	-.189	.217	.370	.105	-.235	.098	.218
	Sig. (2-tailed)	.433	.728	.653	.192	.046	.693		.437	.372	.108	.659	.318	.680	.356
	N	20	20	20	19	20	20	20	19	19	20	20	20	20	20

		Sex	Age	Height	Weight	Average pain during episode	Current pain score	Walking inter-ference score	IPAQ	VAS during experim ent	Stride frequency	Asymm. score	Stride length	Base of support	Actual distance per linear distance
IPAQ	Pearson Correlation	.421	-.415	.449	.370	-.088	.191	-.189	1	**.466 (*)**	.009	.116	-.180	.341	.147
	Sig. (2-tailed)	.072	.077	.054	.131	.721	.434	.437		.044	.971	.637	.460	.153	.549
	N	19	19	19	18	19	19	19	19	19	19	19	19	19	19
VAS during experiment	Pearson Correlation	.115	-.232	.129	.068	.056	**.567 (*)**	.217	**.466 (*)**	1	.207	.106	**-.544 (*)**	**.509 (*)**	-.054
	Sig. (2-tailed)	.639	.338	.598	.789	.820	.011	.372	.044		.395	.667	.016	.026	.826
	N	19	19	19	18	19	19	19	19	19	19	19	19	19	19
Stride frequency	Pearson Correlation	.246	**.533 (*)**	.127	**.668 (**)**	-.002	-.022	.370	.009	.207	1	-.278	-.371	.002	.021
	Sig. (2-tailed)	.296	.015	.594	.002	.993	.928	.108	.971	.395		.236	.108	.992	.929
	N	20	20	20	19	20	20	20	19	19	20	20	20	20	20
Asymm. score	Pearson Correlation	-.069	-.392	.011	-.099	.325	-.198	.105	.116	.106	-.278	1	-.085	-.043	.314
	Sig. (2-tailed)	.772	.087	.964	.685	.163	.402	.659	.637	.667	.236		.722	.856	.177
	N	20	20	20	19	20	20	20	19	19	20	20	20	20	20
Stride length	Pearson Correlation	.406	.005	.366	.246	-.352	-.283	-.235	-.180	**-.544 (*)**	-.371	-.085	1	.069	-.007
	Sig. (2-tailed)	.076	.982	.113	.309	.128	.227	.318	.460	.016	.108	.722		.774	.978
	N	20	20	20	19	20	20	20	19	19	20	20	20	20	20
Base of support	Pearson Correlation	**.496 (*)**	-.029	.219	.450	.103	.332	.098	.341	**.509 (*)**	.002	-.043	.069	1	-.224
	Sig. (2-tailed)	.026	.903	.355	.053	.664	.153	.680	.153	.026	.992	.856	.774		.343
	N	20	20	20	19	20	20	20	19	19	20	20	20	20	20
Actual distance per linear distance	Pearson Correlation	.098	-.143	-.053	.005	.389	-.172	.218	.147	-.054	.021	.314	-.007	-.224	1
	Sig. (2-tailed)	.681	.547	.824	.983	.090	.468	.356	.549	.826	.929	.177	.978	.343	
	N	20	20	20	19	20	20	20	19	19	20	20	20	20	20

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Discussion

It was hypothesized that priming the participants with pain-related concepts would lead to slower, more guarded movements in comparison to cognitive distraction condition. No differences in any of the the motion capture variables characterizing the walking behaviour by the participants in control, cognitive distraction, or pain priming conditions were found, however. There are several possible reasons for this. One possible reason is that there is no behavioural representation for being in pain, and that therefore there was nothing that could be activated by priming. The most likely reasons for the failure to detect any effects of priming may be methodological, however.

Self-focused attention has been shown to negate the effects of priming. Merely performing the same task in front of mirror causes the effects of priming to disappear, for instance (see Dijksterhuis & Bargh, 2001). Likewise, drawing the participants' attention to concepts like "I", "me", and "mine" tends to counteract mimicking (van Baaren, Maddux, Chartrand, de Bouter & van Knippenberg, 2003; Bargh & Chartrand, 1999). In our study, simply because of the necessity of making the participants wear the motion capture suit the participants were aware that their motions were being recorded, and this probably focused their attention to the way they moved. If this is the reason, it would follow that studying the effects of priming by motion capture technology should prove very difficult if not impossible. The participants were also able to see their avatar during the motion capture suit calibration after the priming, and also they were given instructions on how to position themselves during the calibration. The participants were asked about the pain they had suffered as well as their mood and pain levels at different points during the experiment, which could have focused their attention on themselves. Finally, self-focusing was likely also provided by the experimental protocol of motion capture, where the participants were told what movements they should do. This probably served to focus the participants' attention on how they are following the

instructions. Some possibilities to try to avoid these self-focusing effects exist, however. The most obvious possibility would be to make the measurements of walking behaviour when the participant is not aware that his motions are being recorded. The priming could be performed in one room, for instance, and then the participant could be sent to walk down the hallway to another room (similar to Bargh, Chen & Burrows, 1996) where another experimenter awaits and the testing and motion capture will commence. By recording the participants walking characteristics during the walk from one room to another one might avoid much of the self-focusing effects the suit and testing situation induces. Another improvement would be to use motion capture technology that avoids the need for frequent and long calibration, so that it would not be necessary to draw the participants' attention to their position after the priming.

Another factor that might act against priming effects in our study is that priming may lead to opposite effects depending on whether prime leads to assimilation or contrast. In assimilation the prime-activated concept becomes assimilated by the person and guides subsequent action to this direction, in contrast activation the prime-activated concept is seen as contrasting to the person, and leads to opposite effect. The contrast activation instead of assimilation appears to be incited especially efficiently by striking, extreme exemplars, e.g. "professors" activates concepts of smart ("professors are smart, like I am smart") and leads to better performance in Trivial Pursuit questions, but "Albert Einstein" provides contrast ("I am not very smart compared to Albert Einstein") and leads to poorer performance (Dijksterhuis & van Knippenberg, 1998). The priming material included words used to describe extremely severe pain. Depending of the intensity and characteristics of the pain the participants had suffered during their pain episodes, priming effects and activation of pain-related behaviour might be triggered for some participants, whereas by making the participants who had suffered only relatively modest pain to compare their pain to very severe forms of pain, contrast effects could

have been induced in these participants, leading to mixed response. Considering that the values in different conditions were very similar, this would require that the priming effect was nearly perfectly matched by contrast effect, however. Thus this explanation seems unlikely.

Final potential complication is that very little is known about how long the priming effects last: in their experiments with Trivial Pursuit questions Dijksterhuis and van Knippenberg (1998) could not observe any decay in the effects of "stupid" priming (poorer performance in answering questions) at 10 min after the priming, when they asked the last set of questions, but one could argue that the repeated testing in between and the participants' poor performance had reinforcing effect on the "stupid" prime. It is not completely clear then that the priming effect would last throughout the condition, or, if it does, that it would not carry over to the next condition. In the current experiments, the need for motion capture suit calibration after the priming may act to dissipate the effects of priming, firstly simply by taking time, closer to 10 min for a few participants, and secondly during the intervening time and the action taken to calibrate the suit the participant is also subjected to other inputs or primes from the environment. In the current experiments carry-over effects seem unlikely, as no differences were seen compared to control condition that was always first, and no statistically significant effect for the order of conditions (pain priming or cognitive distraction second) could be detected.

The cognitive distraction condition also failed to induce significant differences. This is unsurprising as the cognitive distraction was purposefully chosen to be easy enough not to interfere significantly with movements. Hence, if the priming failed to produce any differences, no differences between the priming and cognitive distraction condition would be expected.

In addition to the above limitations in our experimental protocol, there were also problems related to the participant recruitment. Our purpose was to recruit participants who had had a prolonged episode of chronic pain, but who did not currently suffer from pain. Nevertheless, some participants still experienced low levels of pain, and the pain they felt during the movements could have served to cause guarding in all of the conditions and also served to focus their attention to themselves, interfering with the priming effects. As we were mostly interested in the possible presence of the priming effect, not about the mediating factors, we did not attempt to measure the level of pain catastrophizing by the participants, although one might hypothesize that pain priming would be more immersive and efficient for someone with catastrophic views about pain. We only evaluated the mood effects by using PANAS questionnaire.

Although the current study failed to demonstrate any effects, our failure nevertheless provides some direction for future studies. First, because of the difficulties in avoiding self-focused attention when wearing a motion capture suit, the priming effect should probably first be studied separately. For example, the participants could be divided in four conditions, and be shown movies about i) some neutral thing such as manufacture of fibreglass boats, ii) scientific description of physiological mechanisms and consequences of pain, and iii) & iv) a brief documentary of a person with severe pain. In i) & ii) the participants would need to answer questions about the contents of the movies, in iii) they would need to describe the effects the pain had on the life of the person in the movie, and in iv) they should describe what effects in would have on their lives if they had pain similar to that of the person in the movie. Their walking speed and characteristics could be analyzed when they arrive to and leave from the room where the movie is shown. The priming literature would seem to suggest that stereotype priming effect should appear in ii), contrast effect would be expected in iii), and self-focused attention and disappearance of contrast effect in iv). Such an approach could help to

resolve if reminder of pain could act as a prime and if its effects could be avoided by enhanced self-focusing. Such future priming experiments might benefit from analyzing for changes both in the pain-inducible, guarding movements, and in the primarily communicative pain behaviours such as facial gestures and vocal output, for Sullivan et al. (2006) found that the former appeared to be unaffected by the focus of the participants on pain, whereas the latter increased as the participants focused on their pain levels.

Also an alternative approach could be used, rather than using priming to induce mimicry, mimicry could be used in an attempt to induce emotions. Motion capture recordings of happy, joyful, sad, and depressed walking behaviour could be made using actors, and then the participants could be shown their own avatar on top of the recording of the actor's avatar, and the participants could be told (without telling the participants the emotion represented by the avatar) that they are supposed to match their avatar with the other avatar, and the emotion questionnaires could be used before and after the study for self-report, and walking behaviour after leaving the motion capture room could be video-recorded to analyze the effects of these embodiment feedbacks or activations to the participants' walking behaviour and outside evaluator estimates of their emotions. These effects might provide interesting applications not only for motion capture-aided physical therapy but also for gaming industry.

Although this study was not designed for testing the reliability of motion capture in analysis of walking, the limited data available for analysis appears to imply that after correcting the data for sliding artefacts many of the variables computed were reasonably good descriptors of individuals' walking behaviour. The poor correlation between different stretches and between different conditions for the linearity characteristic implies that the walking distance should be much longer, and preferably in a sufficiently open space so that deviation is not limited by walls. Despite the very low pain levels

reported by the participants, some marginal positive correlation with the width for the base of support and marginal negative correlation with stride length were observed, in keeping with the literature, suggesting that the computed walking characteristics might be useful for studying the effects of current pain on walking. Nevertheless, due to the very marginal level of correlation and the very low average VAS score (≈1 on the scale of 0–10) of the participants this would require further study, but it also raises hope that the analysis routines developed in this work could be useful to characterize the walking behaviour of participants with different pain levels.

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Appendices

Appendix 1. The recruitment letter

Dear all,

I am writing to invite you to participate in study aimed at exploring the influence of pain on movements.

If you have experienced an episode of pain we hope you would be interested in taking part in our research. We are particularly interested in people who have suffered from lower back pain, but we welcome everyone with experiences of pain, such as migraines, toothache and pain resulting from surgery or fractured bones.

As part of our study you will be asked to wear several motion capture sensors attached your body with velcro straps, to perform some simple physical exercises (e.g. walking, carrying a bag, standing on one leg) and to fill some questionnaire, and to listen and repeat words while doing the exercises.

Participation in the study will require approximately 70 minutes and you will be given a box of chocolate as a reward.

This study is part of a large EPSRC funded project. More information about this project can be found at this link:

http://www.uclic.ucl.ac.uk/people/n.berthouze/EPain/index.html

If you are interested to participate, please email me: m.alakoskela@ucl.ac.uk

Best wishes,

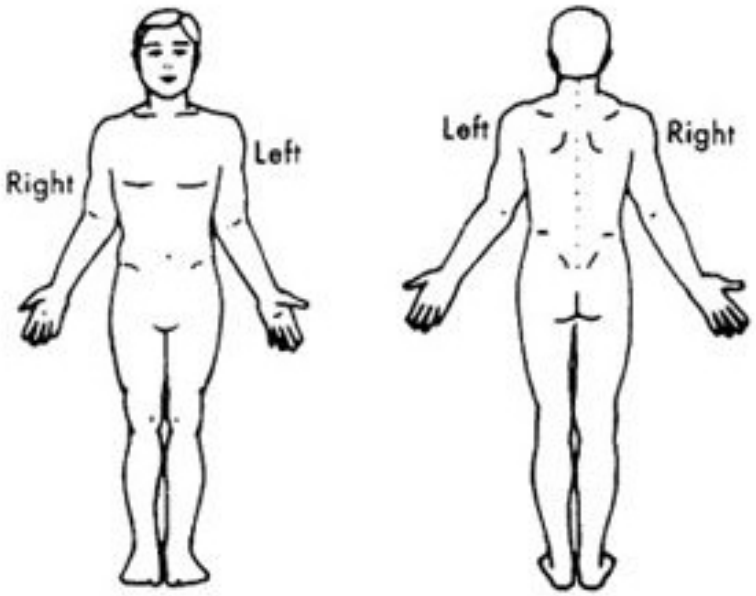
Mirjami Alakoskela

Appendix 2. Pain questionnaire used for pain priming

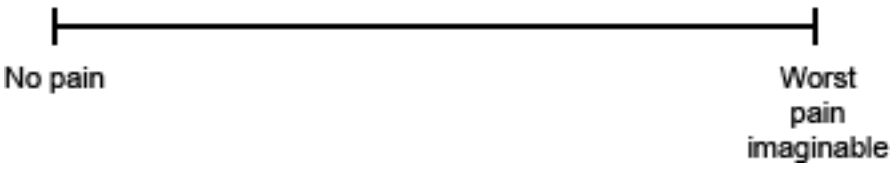
1.) Throughout our lives, most of us have had pain episodes (such as headaches, back pain and pain after physical injuries). What types of pain episodes have you had?

2.) Select one pain episode during which you had significant amount of pain and that you remember well. Describe it. When was it? How did the pain start? What kind of pain it was? How long did it last?

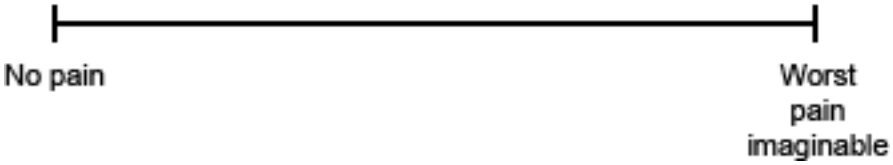
3.) On the diagram shade in the areas where you felt the pain.



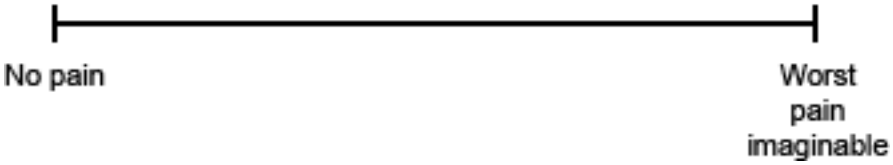
4.) Indicate onto the scale below the position that best describes your pain at its **worst** during the pain episode.



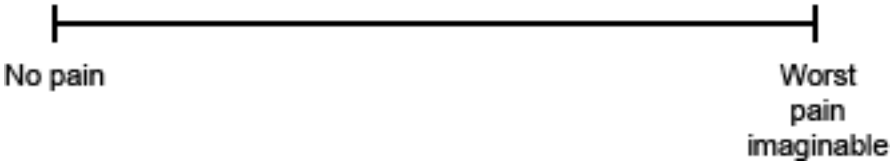
5.) Indicate onto the scale below the position that best describes your pain at its **least** during the pain episode.



6.) Indicate onto the scale below the position that best describes your pain on **average** during the pain episode.

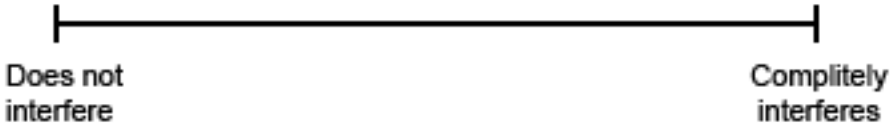


7.) Indicate onto the scale below the position that best describes your pain **at the moment**

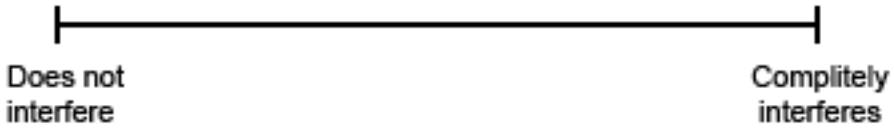


8.) Indicate onto the scale below how much, on its worst, did the pain interfere with your:

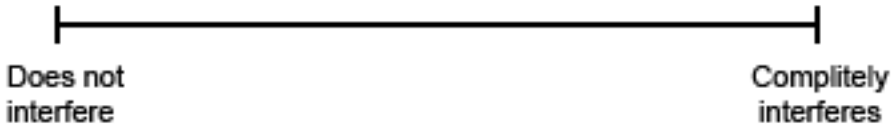
a.) General activity



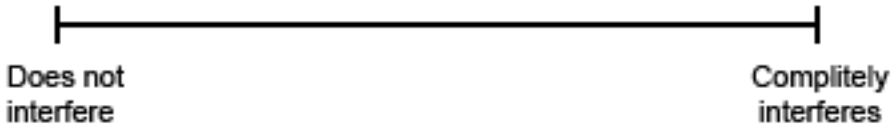
b.) Mood



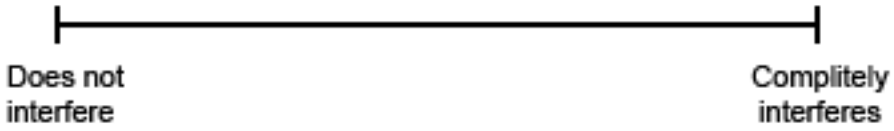
c.) Walking ability



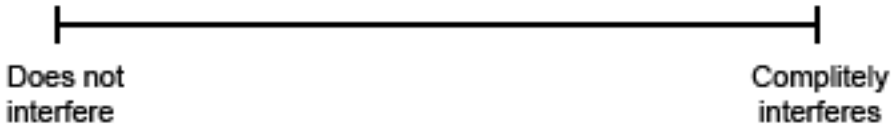
d.) Normal work / studies



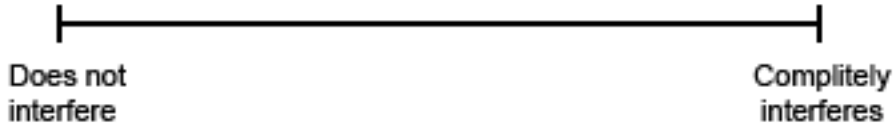
e.) Relations with other people



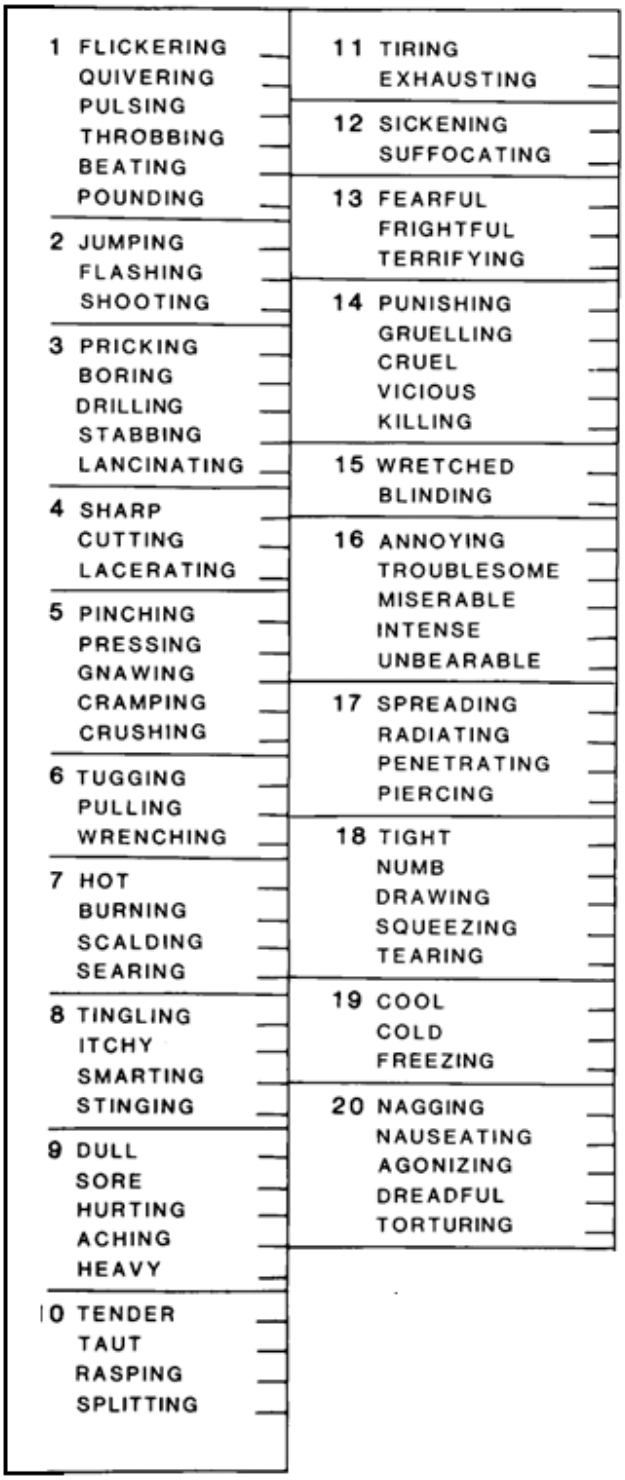
f.) Sleep



g.) Enjoyment of life

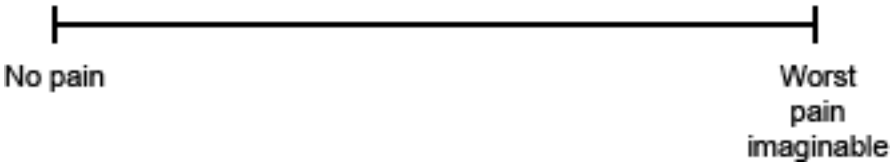


9.) If you think about the pain episode, what did the pain feel like? Mark those words on the list that best describe the pain you had.


1 FLICKERING
QUIVERING
PULSING
THROBBING
BEATING
POUNDING
2 JUMPING
FLASHING
SHOOTING
3 PRICKING
BORING
DRILLING
STABBING
LANCINATING
4 SHARP
CUTTING
LACERATING
5 PINCHING
PRESSING
GNAWING
CRAMPING
CRUSHING
6 TUGGING
PULLING
WRENCHING
7 HOT
BURNING
SCALDING
SEARING
8 TINGLING
ITCHY
SMARTING
STINGING
9 DULL
SORE
HURTING
ACHING
HEAVY
10 TENDER
TAUT
RASPING
SPLITTING
11 TIRING
EXHAUSTING
12 SICKENING
SUFFOCATING
13 FEARFUL
FRIGHTFUL
TERRIFYING
14 PUNISHING
GRUELLING
CRUEL
VICIOUS
KILLING
15 WRETCHED
BLINDING
16 ANNOYING
TROUBLESOME
MISERABLE
INTENSE
UNBEARABLE
17 SPREADING
RADIATING
PENETRATING
PIERCING
18 TIGHT
NUMB
DRAWING
SQUEEZING
TEARING
19 COOL
COLD
FREEZING
20 NAGGING
NAUSEATING
AGONIZING
DREADFUL
TORTURING

Appendix 3. VAS

Indicate onto the scale below the position that best describes your pain **during the last set of exercises**



Appendix 4. PANAS in the beginning of the experiment

This scale consists of a number of words that describe different emotions.

Read each item and indicate to what extent you feel this way **at the moment.**

	1 Very slightly or not at all	2 A little	3 Moderately	4 Quite a bit	5 Extremely
Interested					
Distressed					
Excited					
Upset					
Strong					
Guilty					
Scared					
Hostile					
Enthusiastic					
Proud					
Irritable					
Alert					
Ashamed					
Inspired					
Nervous					
Determined					
Attentive					
Jittery					
Active					
Afraid					

Appendix 5. PANAS after pain priming and cognitive distraction conditions

This scale consists of a number of words that describe different emotions.

Read each item and indicate to what extent you felt this way **during the last set of exercises.**

	1 Very slightly or not at all	2 A little	3 Moderately	4 Quite a bit	5 Extremely
Interested					
Distressed					
Excited					
Upset					
Strong					
Guilty					
Scared					
Hostile					
Enthusiastic					
Proud					
Irritable					
Alert					
Ashamed					
Inspired					
Nervous					
Determined					
Attentive					
Jittery					
Active					
Afraid					

Appendix 6. International Physical Activity Questionnaire (IPAQ) with extra questions (8–12)

Think about all the **vigorous** activities that you did in the **last 7 days**. **Vigorous** physical activities refer to activities that take hard physical effort and make you breathe much harder than normal. Think *only* about those physical activities that you did for at least 10 minutes at a time.

1. During the **last 7 days**, on how many days did you do **vigorous** physical activities like heavy lifting, digging, aerobics, or fast bicycling?

_____ **days per week**

☐ No vigorous physical activities → ***Skip to question 3***

2. How much time did you usually spend doing **vigorous** physical activities on one of those days?

_____ **hours per day**

_____ **minutes per day**

☐ Don't know/Not sure

Think about all the **moderate** activities that you did in the **last 7 days**. **Moderate** activities refer to activities that take moderate physical effort and make you breathe somewhat harder than normal. Think only about those physical activities that you did for at least 10 minutes at a time.

3. During the **last 7 days**, on how many days did you do **moderate** physical activities like carrying light loads, bicycling at a regular pace, or doubles tennis? Do not include walking.

_____ **days per week**

☐ No moderate physical activities → ***Skip to question 5***

4. How much time did you usually spend doing **moderate** physical activities on one of those days?

_____ **hours per day**

_____ **minutes per day**

☐ Don't know/Not sure

Think about the time you spent **walking** in the **last 7 days**. This includes at work and at home, walking to travel from place to place, and any other walking that you might do solely for recreation, sport, exercise, or leisure.

5. During the **last 7 days**, on how many days did you **walk** for at least 10 minutes at a time?

_____ **days per week**

☐ No walking → ***Skip to question 7***

6. How much time did you usually spend **walking** on one of those days?

_____ **hours per day**

_____ **minutes per day**

☐ Don't know/Not sure

The last question is about the time you spent **sitting** on weekdays during the **last 7 days**. Include time spent at work, at home, while doing course work and during leisure time. This may include time spent sitting at a desk, visiting friends, reading, or sitting or lying down to watch television.

7. During the **last 7 days**, how much time did you spend **sitting** on a **week day**?

_____ **hours per day**

_____ **minutes per day**

☐ Don't know/Not sure

8. Age? _____

9. Height? _____

10. Weight? _____

11. Are you taking any medication you think might affect your movement?

_____

_____

12. Do you have any physical condition or injury you think might affect your movement?

_____

_____

Appendix 7. Participant characteristics

Ppt#	Sex	Age (y)	Height (cm)	Weight (kg)	Order of conditions	Data used / Cause of rejection
1	M	35	189	83	Ctrl, Pain, Cog	No/PASAT in Cog
2	F	42	159	67	Ctrl, Cog, Pain	Yes
3	F	34	165	53	Ctrl, Pain, Cog	Yes
4	F	21	167	52	Ctrl, Cog, Pain	Yes
5	F	57	163	70	Ctrl, Pain, Cog	Yes
6	F	24	173	60	Ctrl, Cog, Pain	Yes
7	M	65	155	76	Ctrl, Pain, Cog	Yes
8	M	31	183	81	Ctrl, Cog, Pain	Yes
9	M	30	182	96	Ctrl, Pain, Cog	Yes
10	M	43	183	83	Ctrl, Cog, Pain	Yes
11	F	33	175	64	Ctrl, Pain, Cog	Yes
12	M	45	197	91	Ctrl, Cog, Pain	Yes
13	F	18	179	51	Ctrl, Pain, Cog	Yes
14	M	34	187	98	Ctrl, Cog, Pain	No/Guessed the purpose of expt.
15	F	26	163	60	Ctrl, Pain, Cog	Yes
16	F	29	169	90	Ctrl, Cog, Pain	Yes
17	M	25	189	85	Ctrl, Pain, Cog	Yes
18	F	50	163	Not given	Ctrl, Cog, Pain	Yes
19	M	27	183	81	Ctrl, Pain, Cog	Yes
20	F	27	175	73	Ctrl, Cog, Pain	Yes
21	F	26	165	51	Ctrl, Pain, Cog	Yes
22	F	46	170	63	Ctrl, Cog, Pain	Yes
23	F	35	170	64	Ctrl, Pain, Cog	No/Guessed the purpose of expt.

Appendix 8. Description of the data cleaning and an example

To obtain the key variables stride length, the base of support, and the walking linearity characteristic the data needed to be corrected for the sliding before these analyses (note that analyses utilizing only angular coordinates, i.e. stride frequency and asymmetry variable analysis, are unaffected by the corrections). The first correction that was applied was to simply lock the lowest body part to maintain its position whilst it remains the lowest body part, i.e. subtract the movement of the lowest body part in the XY plane from the movement of the root body part (hips). In other words, the computation was done as follows:

$$H_{i+1}^{C} = H_{i}^{C} + \left(H_{i+1}^{O} - H_{i}^{O}\right) - G\left(F_{i+1}^{O} - F_{i}^{O}\right)$$

where H_i^C is the corrected hip XY coordinate for the i:th data point, H_i^O is the original hip XY coordinate for the i:th data point, F_i^O is the original XY coordinate for the i:th data point for the lowest foot (in Z coordinate), and G is a function that has value 1 if the identity (left or right) of the lowest foot is the same for F_{i+1}^O and F_i^O, and value 0 if the identity is different. Note also that $H_1^C = H_1^O$.

For some recordings the results of this simple procedure were already very good as evaluated by the absence of visible sliding upon visual evaluation of the stick character movies but it failed for other recordings, likely because of sliding at switch points where the identity of lowest body part changed and due to small imprecision in assigning the true lowest body part. Yet, this correction corrected the overall direction of movement for all recordings, i.e. the participants no longer appeared to slide backwards when walking forwards.

As the next step a linear fit (i.e. Y=a+bX) to the spatial coordinates of the walking episode was made using the least squares method to obtain the overall movement direction vector (M), which was taken as the vector connecting initial and final points

on the fitted line. After this, at each data point the foot with slowest velocity component in the direction of overall movement was identified and its movement was subtracted from the movement of hip, the root body part. In other words, the velocity (or differential) vector V at each time point i for each foot was calculated simply as the difference to next data point, calculated the projection length |P| on the overall movement vector M, and used it to select the slowest velocity foot, i.e.

$$V_i^L = L_{i+1} - L_i$$
$$V_i^R = R_{i+1} - R_i$$
$$\left|P_i^L\right| = \frac{V_i^L \bullet M}{\left|M\right|}$$
$$\left|P_i^R\right| = \frac{V_i^R \bullet M}{\left|M\right|}$$
$$V_i^S = \begin{cases} V_i^L, if \left|P_i^L\right| \le \left|P_i^R\right| \\ V_i^R, if \left|P_i^L\right| > \left|P_i^R\right| \end{cases}$$

where V_i^L and V_i^R are the velocities of the left and right foot, L_i and R_i are the XY coordinates of the left and right foot at the i:th time point, $\left|P_i^L\right|$ and $\left|P_i^R\right|$ are the projection lengths of V_i^L and V_i^R on the overall movement direction vector M, and V_i^S is the velocity of the slowest foot at i:th time point. Then the hip XY coordinates were simply corrected using the formula

$$H_{i+1}^C = H_i^C + \left(H_{i+1}^O - H_i^O\right) - V_i^S$$

where the original hip coordinates are the hip coordinates obtained using the first correction. This second correction applied to results of the first step yielded good results for all recordings (see Supplemental movies using the links at the end of this Appendix). Very small artefactual movement will remain in the data, however, because i) possible real sliding becomes also removed, and ii) because a moving foot will become fixed as stationary if both feet are in reality moving within the time between any two subsequent data points.

To see an example of the sliding correction results, see the Supplemental movies. The supplemental movies are in mpeg2 format in non-standard dimensions, and are best viewed with VLC Media Player on Windows OS.

Supplemental movie 1 contains a participant's unmodified, original motion capture recording displaying extensive sliding artefacts.

Address:

http://dl.dropbox.com/u/3316583/Supplemental_Movie_1_walking_original.mpg

Supplemental movie 2 contains the recording of Supplemental movie 1 when corrected for the sliding artefacts as described in text.

Address:

http://dl.dropbox.com/u/3316583/Supplemental_Movie_2_walking_sliding_corrected.mpg

Appendix 9. Pearson correlation coefficients for left–right asymmetry descriptors between two stretches of walking within conditions

The table shows the Pearson correlation coefficients for left–right asymmetry value d (see Results) between two stretches of walking (forth and back) within conditions. The correlation coefficients for the sensors (e.g. UpLeg rot1) and properties (e.g. angular position amplitude) that were selected for the calculation of combined left–right asymmetry variable based on the arbitrary scoring scheme explained in Results are shown in bold.

	ANGULAR POSITION			ANGULAR VELOCITY		
	A	mean	std	A	mean	std
UpLeg rot3	0.35	0.15	0.37	0.37	0.40	0.55
UpLeg rot1	**0.97**	0.22	**0.95**	0.46	0.30	**0.91**
UpLeg rot2	0.18	0.02	0.00	0.41	-0.06	0.63
Leg rot3	0.35	0.13	0.43	0.31	0.00	0.40
Leg rot1	0.48	0.55	0.34	0.70	-0.03	0.42
Leg rot2	0.34	-0.01	0.41	0.45	0.13	0.42
Foot rot3	0.23	0.01	0.32	0.31	0.01	0.24
Foot rot1	**0.71**	0.18	**0.80**	0.65	0.00	**0.61**
Foot rot2	0.42	0.18	0.32	0.42	-0.04	0.41
Shoulder rot3	**0.55**	0.31	**0.51**	0.67	0.03	**0.86**
Shoulder rot1	0.23	0.01	0.44	0.61	0.11	0.76
Shoulder rot2	0.02	0.24	0.12	0.37	-0.04	0.68
Arm rot3	0.36	0.09	0.37	0.55	0.01	0.69
Arm rot1	**0.71**	-0.03	**0.72**	0.62	0.05	**0.78**
Arm rot2	0.47	-0.04	0.57	0.42	-0.10	0.70
ForeArm rot3	0.49	0.07	0.57	0.35	0.01	0.50
ForeArm rot1	**0.53**	0.32	**0.60**	0.44	-0.10	**0.67**
ForeArm rot2	0.03	0.14	-0.08	0.30	0.01	0.32
Hand rot3	0.13	0.88	0.09	0.18	-0.01	0.22
Hand rot1	0.54	0.45	0.65	0.48	-0.02	0.57
Hand rot2	0.42	0.15	0.35	0.38	-0.10	0.68

Appendix 10. Correlations between various collected variables

	height	weight	worst pain during episode	average pain during episode	current pain	general activity inter-ference score	mood inter-ference score	walking inter-ference score	PA	NA	IPAQ	VAS during experiment	stride frequency	asymmetry score	stride length	base of support	actual path / linear path
age	-0.34	0.25	-0.30	-0.11	0.04	0.11	0.00	0.08	-0.06	0.05	-0.41	-0.23	0.53	-0.39	0.01	-0.03	-0.14
actual path /linear path	-0.05	0.01	0.17	0.39	-0.17	-0.02	0.01	0.22	0.32	-0.08	0.15	-0.05	0.02	0.31	-0.01	-0.22	
base of support	0.22	0.45	0.22	0.10	0.33	0.21	-0.13	0.10	0.12	0.11	0.34	0.51	0.00	-0.04	0.07		
stride length	0.37	0.25	-0.30	-0.35	-0.28	-0.07	-0.08	-0.24	0.03	0.14	-0.18	-0.54	-0.37	-0.08			
asymmetry score	0.01	-0.10	0.20	0.32	-0.20	0.21	0.21	0.11	-0.08	-0.14	0.12	0.11	-0.28				
stride frequency	0.13	0.67	-0.18	0.00	-0.02	0.23	0.03	0.37	0.08	0.08	0.01	0.21					
VAS during experiment	0.13	0.07	0.17	0.06	0.57	0.16	-0.22	0.22	0.01	0.02	0.47						
IPAQ	0.45	0.37	0.24	-0.09	0.19	-0.20	-0.22	-0.19	-0.02	0.10							
NA	0.39	0.27	-0.14	-0.17	0.31	0.14	0.13	0.29	0.24								
PA	-0.09	-0.01	-0.03	0.27	0.50	0.04	-0.15	0.26									
walking interference score	0.11	0.31	0.48	0.45	0.09	0.84	0.59										
mood interference score	0.08	0.11	0.59	0.27	-0.21	0.71											
general activity interference score	0.15	0.26	0.52	0.29	0.02												
current pain	-0.35	-0.10	-0.05	-0.09													
average pain during episode	-0.19	0.07	0.64														
worst pain during episode	0.03	0.11															
weight	0.55																