Virtual Reality and Musculoskeletal Pain: Manipulating Sensory Cues to Improve Motor Performance During Walking

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Abstract

Musculoskeletal pain (MSP) is the most expensive non-malignant health problem and the most common reason for activity limitation. Treatment approaches to improve movement without aggravating pain are urgently needed. Virtual reality (VR) can decrease acute pain, and also influence movement speed. It is not clear whether VR can improve movement speed in individuals with MSP without aggravating pain. This study investigated the extent to which different audio and optic flow cues in a VR environment influenced walking speed in people with and without MSP. A total of 36 subjects participated, 19 with MSP and 17 controls. All walked on a motorized self-paced treadmill interfaced with a 3-dimensional virtual walkway. The audio tempo was scaled (75%, 100% and 125%) from baseline cadence, and optic flow was either absent, or scaled to 50% or 100% of preferred walk speed. Gait speed was measured during each condition and pain was measured pre- and post-experiment.

Repeated measures ANOVA showed that audio tempo above baseline cadence significantly increased walk speed in both groups ($F(3,99)=10.41$ $p<0.001$). Walking speed increases of more than 25% occurred in both groups in the 125% audio tempo condition, without any significant increase in pain. There was also a trend towards increased walk speeds with the use of optic flow, but the results in this study did not achieve significance at the $p<0.05$ level ($F(2,66)=2.01$ $p=0.14$).

Further research is needed to establish the generalisability of increasing movement speed across different physical performance tasks in VR.

Introduction

Pain remains a pervasive, complex, and challenging phenomenon associated with tremendous human and financial costs. Musculoskeletal pain is the most expensive non-malignant health problem affecting the working age population and is the most common reason for activity limitation. In the United States, chronic pain is estimated to affect 100 million adults and costs $560-635 billion annually[1] . Although pain is frequently a symptom of tissue injury or illness, persistent pain is now also recognized as a disease per se [2]. Regardless of its genesis, pain is associated with compromised mood and movement across health conditions.

Generalized psychomotor slowing is commonly associated with pain, as individuals appear to have difficulty generating or withstanding the relatively higher forces associated with faster movements. Psychomotor slowing frequently persists despite the apparent resolution of injury or illness. This failure to resume usual movement speed leads to prolonged reduction in activity and increased disability[3, 4]. Research has shown that individuals with pain and illness can move faster when challenged to but tend not to if unchallenged [5]. Thus therapeutic approaches that enhance movement speed without increasing perceived pain or effort may help patients recalibrate their expectations and subsequently resume optimal and efficient movement speeds that decrease disability.

The benefits of Virtual Reality (VR) for rehabilitation are known to include increased engagement with therapy [6-8] and distraction from pain [9-10]. If this ability of VR to distract from pain can be leveraged whilst employing techniques to facilitate faster movement, it could offer significant potential for locomotor rehabilitation for conditions associated with MSP.

VR and Analgesia

Evidence from a number of studies has demonstrated an analgesic effect of virtual reality for acute pain, primarily with pain due to burns or medical procedures [9-10], but the effect on active movement was not assessed. Furthermore, a recent systematic review reported strong evidence for the analgesic effect of immersive VR on acute pain in adults, but found insufficient evidence supporting the effectiveness of VR for reducing chronic pain[12]. Thus whilst it is clear that VR may be useful for the amelioration of pain in some settings, it is not known how patients with chronic MSP might respond, particularly during active motion which would normally elicit increased levels of perceived pain.

To date the mechanisms that account for a potential analgesic effect of VR are not clear but are probably due in part to VR affording a means of attracting an individual’s attention towards an alternative visual and auditory stimulus and thereby reducing the magnitude of attention available to focus on pain. Moreover, given that attention to visual and auditory stimuli in VR limits attention to pain stimuli, it is plausible that the addition of movement during VR could demand even more attention and thereby further enhance analgesia – or at least not allow for an increase in pain related to movement.

VR to improve walking speed

Applications to support walking in VR generally use a treadmill or similar device, interfaced to the VR software to create the illusion of moving through the virtual environment [11, 13]. Fixed pace treadmills are known to disrupt the spatio-temporal control of gait [14], and self-paced treadmills interfaced to Virtual Reality are increasingly widely used [11, 13], as they support the natural walking ratio [14]. However, they also tend to be associated with a decrease in walking speed when users are free to self-select their own pace [13-15], and this is true both for healthy adults and for patients with musculoskeletal pain [14]. Thus if the analgesic effect of virtual reality and the natural walking support of the self-paced treadmill are to be leveraged for effective rehabilitation protocols they need to be combined with techniques to facilitate or encourage increased walking speeds.

Optic flow (the apparent motion of objects, surfaces, and edges in a visual scene caused by the relative motion between an observer or virtual camera and the scene) is used as a powerful cue to determine self motion. It has previously been demonstrated that altering the rate of optic flow in a virtual environment can influence walking speeds in a healthy population, with lower flow rates being associated with faster walking speeds [15-17], but this has not yet been demonstrated in patients with pain. However, it is plausible that the slowing of optic flow rate, and the associated reduction in perceived self-motion, may reduce the fear of pain associated with increased walking speeds in people with musculoskeletal pain, reducing the inhibitory effect of anticipatory pain on walking.

In addition, there is a strong link between auditory rhythms and motor activity, and the motor system is physiologically sensitive to arousal by the auditory system [18]. A number of studies in non-VR settings indicate that the use of audio cues can facilitate improved walk speed and quality [19-22], and more recently it has been demonstrated that this audio cue facilitating effect can also be seen in treadmill-mediated VR [23]. Not only has this effect been seen in healthy populations, there is also data to suggest that audio cues can improve walk speed and cadence in Parkinson's Disease [20, 22,24- 26] and also in stroke patients [19, 21]. However, both

Parkinson's disease and stroke are associated with neurological deficits resulting in motor dysfunction, and it cannot be assumed that similar facilitation would be observed in populations with musculoskeletal pain, where slow movement has a less direct neurological aetiology. Furthermore, chronic pain demands a high level of attention, which may distract attention from other tasks [3, 27], and therefore it may be the case that patients with chronic pain would be less able to attend to the visual and auditory cues that would otherwise lead to faster walking speeds.

The purpose of this study was to examine the extent to which audio and visual cues in treadmill-mediated VR can increase gait speed for people with slowed movement due to pain.

Materials and Methods

Previous work identified that presenting an optic flow speed of 0.5 x normal (non-VR) walk speed was associated with a significant increase in walk speed[15], and so this was selected as a level for this experiment. To provide a comparison and control, two other visual conditions were also included, optic flow matched to baseline treadmill walk speed[1], and absent optic flow (static image). The experiment used a virtual environment which was designed to provide high contrast peripheral visual cues to improve self-motion perception[28] without any central visual clutter or obstacles[29]. The audio cue rates were scaled from the baseline cadence using the same scaling as in our previous work (75%, 100% and 125% of baseline cadence)[23].

The experimental design was a mixed 3 x 4 x 2 factorial experiment with two within-subjects factors (optic flow x audio) (Table 1),

[1] Prior to conducting the experiments, all participants were familiarised with the self-paced treadmill, and when they were able to maintain a steady speed and cadence they completed a 3-minute treadmill walk test, with no audio or visual cues. Average walk speed and cadence were recorded, and used as baseline measures for the experimental cue conditions.

TABLE 1: THE COMBINATION OF AUDIO AND VISUAL CUES FOR THE EXPERIMENTAL CONDITIONS FOR THE TWO EXPERIMENTAL GROUPS

	No audio	**audio rate 75% baseline cadence**	**audio rate 100% baseline cadence**	**audio rate 125% baseline cadence**
No optic flow	condition 1	condition 4	condition 7	condition 10
optic flow 50% baseline speed	condition 2	condition 5	condition 8	condition 11
optic flow 100% baseline speed	condition 3	condition 6	condition 9	condition 12

and one between subjects factor (pain). Audio cue tempo, optic flow rate and presence of pain were the independent variables. Walk speed was the dependent variable. In addition, the pre-and post- experiment pain intensity and pain affect were recorded as dependent variables for the musculoskeletal pain group.

Apparatus

The treadmill used in this study was a self-paced motorised treadmill [30]. The treadmill responded dynamically to the speed of the user in real time. The belt speed was recorded to a computer using an optical sensor at a resolution of 0.01m/s.

The treadmill was placed 1.5m in front of a 2.44m wide x 3.05m high screen. A 3-dimensional model of a virtual walkway was created using SoftImage XSI software. The scene consisted of two parallel rows of vertical columns on either side of a walkway (Figure 1).

The virtual camera was set to match the starting position of the participant, with a horizontal field of view of 80^{o} and a height of 1.6m above the ground plane. The scene was back-projected onto the screen using a single (monoscopic) projector. To minimise visual distraction, the room was darkened for the experiment, with the main light source being the display screen itself.

Figure 1: The high contrast walkway with vertical peripheral cues used to generate the optic flow

CAREN D-flow software (Computer Assisted Rehabilitation Environments, Motek BV) was used to control the hardware system and synchronize the instantaneous treadmill speed and scene progression via a software gearing module. The audio component was also synchronised by the D-flow software. The audio was the sound of a footstep on a hard surface, loaded as a .wav file into application. The sample sound was 0.2 seconds long, sampled at 705 kbps. It was delivered to the participant via Logitech ClearChat™ wireless stereo headphones.

Participants

A total of 36 volunteers participated in the experiment. Patients with musculoskeletal pain on walking were recruited from the Jewish Rehabilitation Hospital (Laval, Quebec) and the Constance Lethbridge Rehabilitation Centre (Montreal, Quebec). Healthy volunteers were recruited from the staff and student body of the Jewish Rehabilitation Hospital (Laval, Quebec), the Constance Lethbridge Rehabilitation Centre (Montreal, Quebec) and McGill University (Montreal, Quebec).

The participants were assigned to one of two groups based on the presence (n=19) or absence (n=17) of musculoskeletal pain in the upper or lower limb that compromised walking

(Table 2). All were able to walk independently and had no other medical condition which limited walking (e.g. stroke, Parkinson's disease, heart disease etc).

TABLE 2: DEMOGRAPHIC DETAILS OF PARTICIPANTS

	Age	Gender	Pain intensity	Pain affect
No pain (N=17)	22 - 68 mean 46.9	8 female 9 male	N/A	N/A
Pain (N=19)	24 - 80 mean 54.8	13 female 6 male	mean 3.9(2.5)	mean 2.8(2.8)
Pain intensity and pain affect scored on a 1-10 numeric rating scale (NRS) on day of testing (StDev				

Ethical approval was obtained from the Comité d'éthique de la recherche des établissements du CRIR (Montreal, Canada). All participants were able to converse fluently in either English or French, and gave their informed consent prior to inclusion in the study.

Procedure

The participants walked in each of the experimental conditions in a counterbalanced order. For the visual cues, the preferred walk speed was used to scale the optic flow by a factor of 0, 0.5 or 1, and the rate of apparent motion through the virtual environment was maintained at this speed for the duration of the trial. For the audio cues, the baseline cadence was used to scale the audio tempo by a factor of 0, 0.75, 1 or 1.25, and the footstep beat was played at this tempo for the duration of the trial.

During pilot testing, it was found that 2 minutes of walking was sufficient to obtain consistent walk speed data, and therefore each of the trials was limited to 2 minutes duration.

For each of the trials, the participants were asked to walk at their preferred (baseline) speed on the treadmill. At the start of each trial, treadmill walking was initiated in the absence of optic flow or audio. When participants reached 75% of their preferred walk speed, the visual / audio cues for the trial condition were initiated automatically. The participants then continued to walk on the treadmill for 2 minutes, whilst being presented with the combinations of audio and visual cues. The participants were able to rest between trials as required, and completed a total of twelve 2-minute trials.

Participants were instructed to walk at a self-selected pace for the duration of each 2 minute trial. No instructions were given regarding whether or not they should attempt to synchronise with the audio beat.

Participants from the pain group were asked to notify the experimenters of any significant change in pain, and to give a verbal Numeric Rating Scale (NRS) rating of perceived pain intensity and pain affect immediately after completing the experiment.

Results

The effect of audio and visual cues on walk speed

The walk-speed of the participants was automatically recorded to the treadmill control computer during each trial, and the mean walk speed (m/s) was calculated from this data (Table 3). A repeated measures ANOVA (optic flow x audio cue tempo x pain) demonstrated a significant effect of audio tempo on walk speed ($F_{(3,99)}=10.41$ $p<0.001$), but no significant effect of optic flow on walk speed ($F_{(2,66)}=2.01$ $p=0.14$).

TABLE 3: OVERALL MEAN WALK SPEEDS (M/S) IN EACH OF THE EXPERIMENTAL CONDITIONS (STDEV IN BRACKETS)

	No audio		**audio rate 75% baseline cadence**		**audio rate 100% baseline cadence**		**audio rate 125% baseline cadence**	
	Pain	*No pain*	*Pain*	*No pain*	*Pain*	*No pain*	*Pain*	*No pain*
No optic flow	0.88 (0.33)	1.08 (0.30)	1.10 (0.35)	1.47 (0.28)	1. 07 (0.41)	1.37 (0.35)	1.12 (0.40)	1.40 (0.29)
optic flow 50% baseline speed	1.06 (0.36)	1.39 (0.24)	1.04 (0.38)	1.38 (0.33)	1.06 (0.34)	1.36 (0.30)	1.09 (0.34)	1.46 (0.28)
optic flow 100% baseline speed	1.06 (0.39)	1.37 (0.26)	1.08 (0.29)	1.33 (0.30)	1.03 (0.36)	1.22 (0.48)	1.09 (0.36)	1.36 (0.28)

Although there was no statistically significant effect of optic flow, there was a trend towards increased walking speeds when the treadmill was linked to the virtual environment particularly in the non-pain group and the slow optic flow condition, with >20% mean walk speed increases (Figure 2).

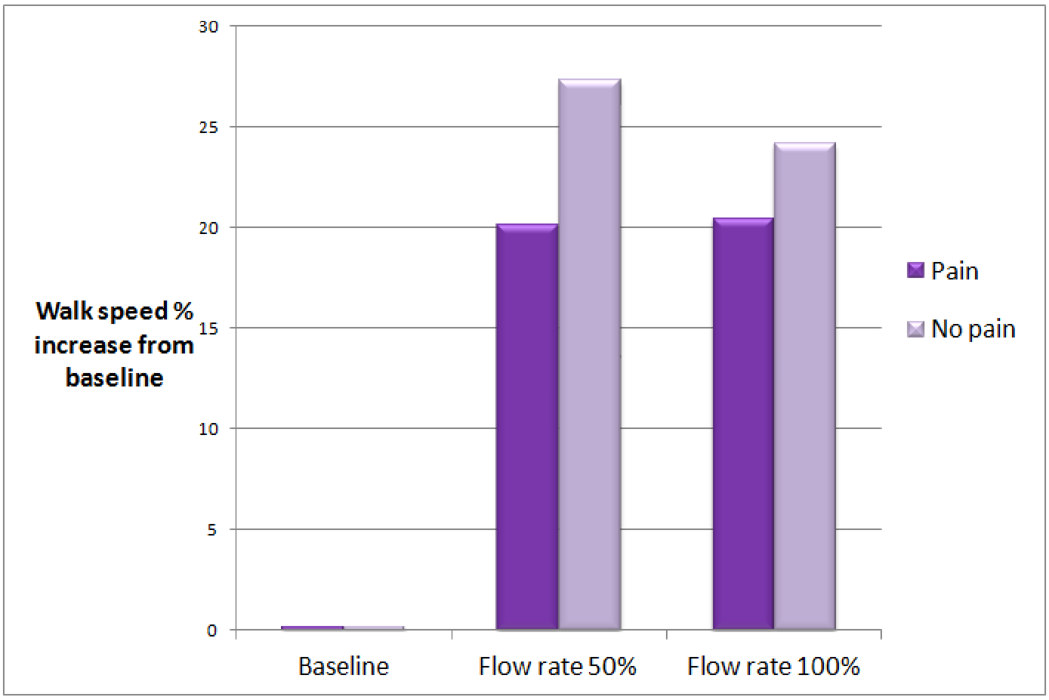

Figure 2: The percentage increase in mean walk speed from baseline with varying optic flow rates

Post hoc analysis revealed that the walk speed in the fast audio condition was significantly faster than the no-audio condition ($p<0.001$) and faster than the 100% audio condition ($p<0.05$), but was not significantly different from the slow audio condition ($p=0.3$). The walk speed in the slow audio condition was also significantly faster than in the no-audio condition ($p<0.001$). There was no significant difference between any other pairs of audio conditions. Walk speed in all audio conditions was faster than without audio cues (Figure 3).

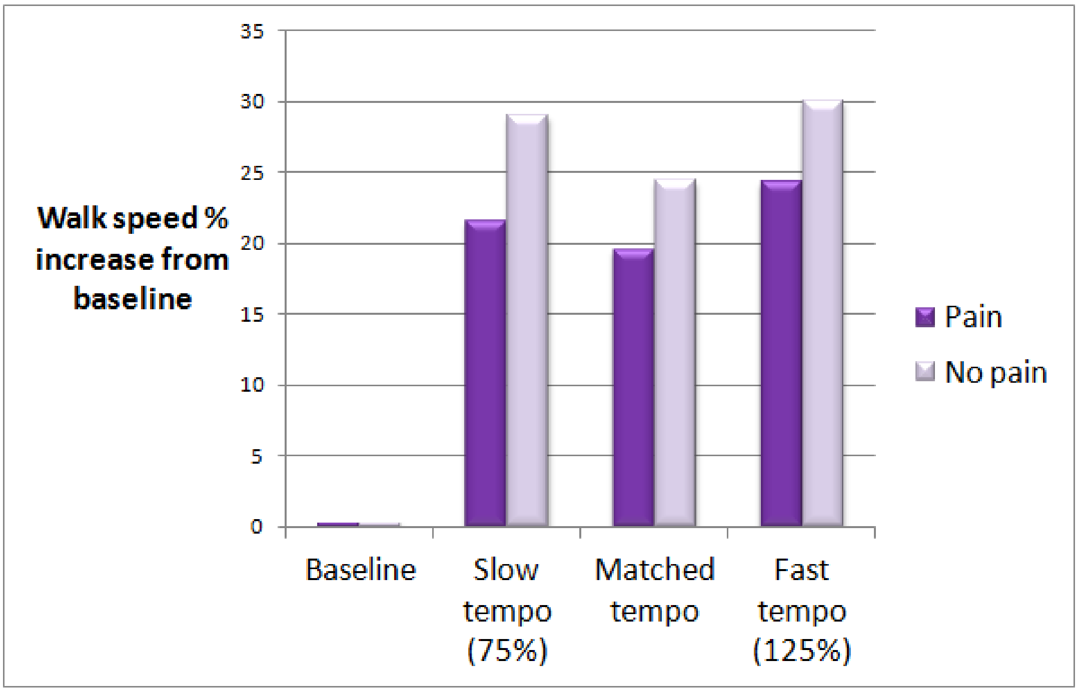

Figure 3: The percentage increase in mean walk speed from baseline with varying audio cue tempo

There was no significant interaction effect ($F_{(1,33)}$=0.074 p=0.79) between pain and audio, and no significant interaction ($F_{(1,33)}$=0.29 p=0.56) between pain and visual cues. However, there was a significant interaction ($F_{(6,198)}$=12.31 p<0.001) between audio and visual cues.

There was a significant difference between the non-pain and pain groups ($F_{(1,33)}$=8.08 p<0.01). The mean walk speed of the pain group was lower than the non-pain group across all conditions.

Comparison of pain at the start and end of the experiment

Repeated measures analysis (paired t-test) showed no significant difference in the pain intensity (t(16 =0.46 p=0.65) or the pain affect (t(16)=2.12 p=0.06) between the beginning and end of the experiment (after 12 trials) for the pain group (Figure 4). Pain intensity and affect were not measured for the non-pain group.

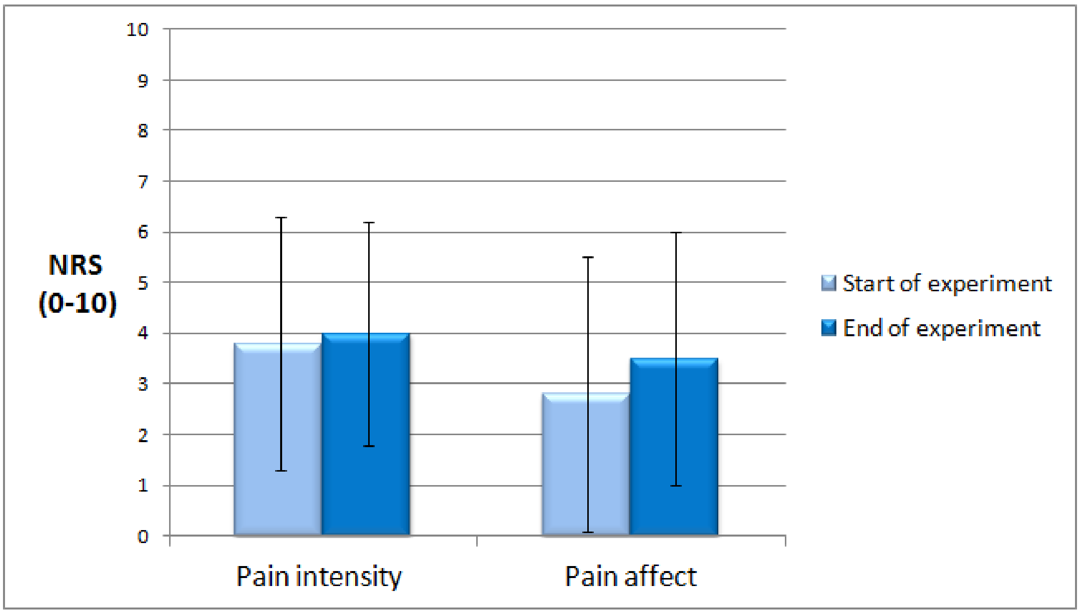

Figure 4: Comparison of pain intensity and pain affect at the start and end of the experiment.

Discussion

The effect of audio and visual cues on walk speed

The use of audio cues above baseline cadence was associated with faster walk speeds in both pain and non-pain groups. There was no difference in the direction or magnitude of the effect between the group with pain and the group without pain. This supports and extends the findings of our previous work [23] and suggests that audio cues may be effective in facilitating faster walking in patients with chronic pain as well as in healthy adults.

It was somewhat surprising to find that the speed increase was similar in both the slow and fast audio cue conditions. However, previous studies have noted the ability to synchronise to twice the speed of a slow tempo ("doubling" the tempo) [31], and this would be consistent with the speed increase seen with this cue frequency, where the response to the 75% tempo is similar to the response to the 125% tempo . Further work is underway to investigate a wider range of audio tempos.

There was a significant interaction between the audio and visual cues, with slower walk speeds when optic flow was present compared with audio alone (no optic flow). This might be explained by the model of competing attentional demands. Auditory and visual stimuli both require attention, which can be considered to be a finite shared resource [27]. In the presence of audio cues alone, there is sufficient attention to respond to the cues, but by adding the visual cues the attention is divided between two cues [22]. Audio cues which are in conflict with the preferred cadence may disrupt the automatic synchronicity of walking, necessitating more conscious attention. The suppression of the effect of audio on walk speed by the addition of optic flow may therefore be attributable to a reduction of attention to the audio cues in the presence of a competing attentional load. However, the data in this experiment does not display a robust enough pattern to be certain of the underlying mechanisms, and further investigation is necessary to establish whether other attentional loads also reduce the influence of audio cues on walking.

In contrast to earlier studies [15-17], altering the optic flow rate did not have a significant effect on walking in either the pain or non-pain populations (although there was a trend towards faster walking speeds in the optic flow conditions compared to a static scene). If this had been noted in just the pain group, it might have been concluded that the presence of pain was sufficient distraction to prevent a normal response to the optic flow. However, neither group demonstrated any significant effect of optic flow rate, and since this is in direct contrast to most previous studies, it warrants some examination of the experimental design. The virtual environment, screen size, treadmill type and optic flow rate were all similar to those used in our previous work [15]. However, due to the equipment constraints in the clinical laboratory, the projection was monoscopic, whereas stereoscopic projection was used previously. It has been noted that depth judgements and self-speed perception in VR are influenced by the use of binocular disparity cues [32, 33], and it may be that the lack of visual depth cues altered the perception of the speed of optic flow, reducing the strength of its effect. A further study comparing the effect of optic flow in mono and stereo virtual environments is required to establish if this is the cause of the unexpected result in this study. If so, it may have significant implications for virtual environment design for rehabilitation applications.

Patients with pain walked on average 21% slower (1.06 m/s) across all conditions than the non-pain group (1.35 m/s), similar to the findings in our previous study with this patient group[14]. However, when the 75% or 125% audio cues were present, in the absence of optic flow, the pain group showed speed increases of up to 27% above their preferred treadmill walk speed, achieving speeds higher than the baseline treadmill walk speed of the non-pain group (Table 3). This supports previous observations that individuals with pain can move faster but don't [4].

In total, the participants in this study undertook around 30 minutes walking, albeit in short blocks, and much of this walking was at or above the preferred (baseline) treadmill walk speed. However, there was no significant increase in reported pain intensity or pain affect. Whilst it would be anticipated that in normal treadmill walking, patients with chronic musculoskeletal pain would notice an increase in pain over time, this study did not have a control MSP group walking on the treadmill without any audio or visual cues. To answer the question as to whether the treadmill-mediated VR suppressed the perception of increased pain, a study comparing a VR intervention with non-VR treadmill walking would be necessary.

The ability to disengage from pain relates to the perceived threat [34], and since patients systematically overestimate the pain associated with fast movements, this may act as a barrier to voluntary increases in speed [4]. Pain demands attention, and chronic pain involves continual switching between pain and other attentional demands [27]. Attending to visual or auditory cues also requires attention, and if this provides a sufficient distraction to enable some disengagement from the pain, then this may reduce the hindrance to faster walking. Indeed, this is supported by the finding that walk speed is higher in all cueing conditions compared with preferred speed measured at the start of the study. Previous studies have demonstrated that immersive VR can reduce perceived pain during passive procedures [35, 36], and the results of this study suggest that it is possible that the pain-reducing properties of VR may also be effective during active rehabilitation procedures.

It is evident that with careful VR design, patients with pain can improve walking speeds to a level commensurate with effective rehabilitation, and this can be achieved without concomitant increases in pain. This demonstrates the potential of VR in the rehabilitation of patients with musculoskeletal pain, and may offer some support in breaking the pain / reduced movement cycle.

Conclusion

Chronic pain (>6 months) can result in a cyclic disability-enhancing pattern of further decreased activity and avoidance that prevents normal restoration of function and perpetuates painful experiences [3], and thus interventions are needed which can distract from or reduce the perceived pain whilst supporting improved movement.

VR offers recognised benefits of increased engagement and decreased pain perception, and it is clear from this study that the manipulation of audio and visual cues in VR can improve walking speed, even in patients with chronic musculoskeletal pain. Incorporating audio cues into a VR application which were presented at a tempo 25% above the normal preferred cadence facilitates increased walking speeds by around 27%, and this was achieved without a significant increase in either pain intensity or pain affect. This improvement in walking appeared to also be influenced by the rate of optic flow, although further work with stereoscopic projection is necessary to properly quantify this effect.

Since both auditory and visual sensory output is an integral component of most virtual rehabilitation system, VR designers should incorporate these factors in a systematic manner to improve rehabilitation outcomes.

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