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Neuroscience Letters 341 (2003) 167–169

Neuroscience Letters

www.elsevier.com/locate/neulet

Increased motor control of a phantom leg in humans results from the visual feedback of a virtual leg

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Received 27 November 2002; accepted 27 January 2003

Abstract

Although previous research reported that the visual feedback of a 'virtual arm' increased the control of a phantom arm, it did not consider that the repeated attempt to move the phantom may have contributed to the effect. Twenty-one lower limb amputees reported the response of their phantom leg during repeated attempts to move both legs in one of two conditions, a control condition in which the amputee only viewed the movements of their intact leg and an experimental condition in which the amputee additionally viewed the movements of a 'virtual' leg. It was found that viewing a virtual leg resulted in amputees reporting a significantly greater number of movements of their phantom leg than with attempted movement alone. The implications were discussed in terms of visuo-motor adaptation and theories of motor control.

Keywords: Virtual limbs; Amputation; Phantom limb movement; Increased use

Phantom limb pain is a major cause of distress, physical limitation and disability in approximately 85% of amputees [5] with a lack of any successful treatment despite numerous surgical, pharmacological and physical methods [12]. A phantom limb is thought to be experienced because the same brain processes that generate the experience of an existing limb remain present following amputation [7], a view further confirmed by numerous brain imaging studies [3,13]. However, phantom limb pain may depend upon pathological changes [14]. It is surprising therefore that given the importance of vision in controlling the movement of upper [4] and lower limbs [9], little research has been carried out into the possible interaction between vision and the control of movement of a phantom limb.

It has been reported that vision can interact with the experience of a phantom arm using a 'virtual limb' box in which the reflection of the amputees' intact arm is superimposed upon the felt position of their phantom arm [10,11]. It was found that viewing this 'virtual limb', whilst sending commands to move both limbs, induced a number of effects in the phantom including movement and alleviation of pain. However, there was a methodological problem with these studies: the experimental condition, in which there was visual feedback of the moving virtual arm, whilst attempting to move the phantom arm, was repeatedly administered. On the other hand the control condition, in which there was an attempt to move the phantom arm without any visual feedback, was administered only once. As it has been reported that phantom limb exercise may in itself reduce phantom limb pain [14] and that the use of a functional prosthesis may reduce phantom limb pain in upper limb amputees [16], the visual feedback of a moving virtual limb need not have been the cause of the reduction in pain. Furthermore, the inability to move a phantom limb may be due to learned non-use. This condition has been reversed in post stroke patients with upper limb weakness by constraint induced movement therapy in which patients are encouraged to move their affected limb [15].

As lower limb amputees are by far the larger proportion of the amputee population, the extent to which visual feedback of a virtual leg modifies the experience of a phantom leg requires investigation. For example, in the UK there were 4959 new lower limb amputees and 254 new upper limb amputees during the year 1999–2000 [8]. The purpose of this study is to establish empirically, using a randomized controlled trial, whether it is the visual

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0304-3940/03/$ - see front matter © 2003 Elsevier Science Ireland Ltd. All rights reserved.
doi:10.1016/S0304-3940(03)00160-5

feedback of a virtual limb, or the repeated attempt to move the phantom limb, that alters the experience of a phantom leg in lower limb amputees.

Twenty-one lower limb amputees attending the Artificial Limb and Appliance Centre, Southern General Hospital for limb fitting were invited to participate in this study and informed consent was obtained. A virtual limb box (640 mm depth × 630 mm width × 900 mm height) was constructed of wood; it was open at the front and top with a central mirror (640 mm × 900 mm) positioned vertically half way between the box sides. This allowed the mirror to be aligned in the saggital plane of each subject, with the intact limb placed to one side and the subject able to look down on the mirror to view a 'virtual' limb. The side of the box in which the phantom limb was placed was obscured. Subjects were randomly assigned to one of two conditions. In the experimental condition, the subject was asked to place their intact limb into the mirror box, direct their gaze onto the mirror image of their intact limb and align their phantom with this image. In the control condition the mirror was obscured which allowed the subject to view the intact limb but not its mirror image. In both conditions the subject was instructed to attempt to carry out the following ten movements each ten times with both phantom and intact limbs.

1. Slowly straighten and then bend your legs at the knee at the same time.
2. Slowly straighten and then bend your legs at the knee alternately as if walking.
3. Point your feet upwards, and then point your feet downwards at the same time.
4. Turn your soles in towards each other and then away from each other.
5. Move your feet around in a circle, to the left and to the right.
6. Lift your feet off the ground in a walking movement.
7. Point your toes upwards, and then downwards whilst trying to keep your ankle and foot still.
8. Clench and unclench your toes.
9. Spread out your toes and then relax them.
10. Point up your big toe and point down the other toes, then reverse it so that your big toe is pointing down and your other toes are pointing up.

There was a pause between each type of movement and if at any point the subject felt unable to continue and wished to stop, the procedure was discontinued. This did not happen for any of the subjects. During the performance of the movements the subjects were instructed to describe verbally any changes they experienced in their phantom limb. These responses were recorded onto an audio cassette and were subsequently scored in terms of the number of phantom leg movement responses to each of the ten movements. The patient sample (see Table 1) consisted of 16 males and five females. The median age was 46 years (range 31–83 years) and the median time since amputation was 7 years (range 1–48 years). Ten were right-sided and 11 were left-sided amputation, with 11 trans-femoral and ten trans-tibial. In the experimental group ($n = 11$; m = 9; f = 2), seven were right-sided and four were left-sided amputation with three trans-femoral and eight trans-tibial. In the control group ($n = 10$; m = 7; f = 3), three were right-sided and seven were left-sided amputation, with eight trans-femoral and two trans-tibial. There were no significant differences between the experimental and the control group for gender, age, time since amputation or self reported control of the phantom leg. The mean number of movement responses elicited in the phantom limb during the procedure was 6.91 for the experimental group and 2.3 for the control group. This was found to be significantly different using a t-test ($t = 3.147$, d.f. 14.801, $P < 0.01$).

This randomized controlled trial demonstrated that it is the addition of visual feedback of a moving virtual leg in conjunction with the attempted movement of the phantom leg that significantly increases the ability of an amputee to move his/her phantom leg. Although it has been reported that the repeated attempt to move a phantom limb may in itself result in an increase in control and a reduction in pain [14] the provision of visual feedback resulted in a threefold increase in the amount of movement control experienced by amputees.

Whether the visual feedback of a virtual limb contributes to the alleviation of phantom limb pain could not be addressed in this study. This was because at the time of the intervention not one subject was in pain. This was surprising as 95% of the subjects reported having experienced phantom limb pain. Ongoing research with a larger patient population will address the relationship between an increase in the control of a phantom limb and phantom limb pain.

Why the visual feedback of a virtual limb should alter the phantom limb experience remains difficult to explain. Firstly, why should an amputee attribute the reflected image of the intact limb as being that of their amputated leg? In other words, why should they ascribe ownership of the virtual limb to themselves? A number of the subjects reported surprise and a number joked about seeing their leg again. It may be because the cues necessary to support self recognition were present. For example, in mirror studies it has been found that, if visual information signals the correct spatial orientation of a hand and signals the correct movement information subjects ascribe the image of a hand to themselves. However, when movement information is absent, subjects have difficulty in ascribing ownership of the hand [2]. In this study both spatial and movement cues were present. Amputees aligned their phantom limb spatially to the mirror image and their intact and virtual limbs moved appropriately in response to the motor commands issued. Secondly, why should seeing a virtual limb move have any effect upon the phantom limb? This may reflect some of the processes involved in visual-motor adaptation, particularly the primary role vision plays in

Table 1
Subject details

	Total ($n = 21$)	Treatment ($n = 11$)	Control ($n = 10$)	Significance
Gender (m/f)	16:5	9:2	7:3	NS
Median age in years (range)	46 (31–83)	44 (31–83)	55.5 (36–80)	NS
Years since amputation (range)	7 (1–48)	9 (1–48)	5.5 (2–23)	NS
Side of amputation	R = 10, L = 11	R = 7, L = 4	R = 3, L = 7	
Position of amputation	TF = 11, TT = 10	TF = 3, TT = 8	TF = 8, TT = 2	
Reason for amputation				
Congenital	2	1	1	
Cancer	2	1	1	
Accident	8	4	4	
Other medical	9	5	4	
Control of phantom				
Total	8	5	3	
Some	5	2	3	NS
None	8	4	4	

TF, trans-femoral; TT, trans-tibial; NS, non-significant.

signalling the position of a limb in situations where there is disparity with proprioception [6]. If the mechanisms underlying the effects of a virtual limb are those involved in visuo-motor adaptation then it would explain why repeated viewing of a virtual limb may be necessary to produce a change in the felt position of a phantom limb. However, it would also predict that a return to the pre-adaptive state would also occur. A longitudinal study using a diary methodology is currently being undertaken to investigate the effects of one treatment upon the phantom limb experience. Thirdly, any explanation has to account for how the conscious experience of movement and position change of a phantom limb following the motor command to move is signalled without proprioceptive feedback. However, such feedback may not be necessary to signal position and movement changes. Blakemore et al. [1] suggested a forward model of motor control that utilizes internal representations of the actual, predicted and desired state of a limb. This allows the position of a limb to be known on the basis of a desired state derived from motor commands in conjunction with visual and/or proprioceptive sensory feedback. Thus, this model explains why the visual feedback of a virtual limb can act with the motor commands to allow the predicted state to be updated and new positions of the phantom limb to be experienced without proprioceptive feedback.

Acknowledgements

This research was supported by the Chief Scientist Office, Scottish Executive, Grant CZG/4/2/61 to Eric E. Brodie and Anne Whyte.

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