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

Eric E. Brodie\textsuperscript{a,}\*, Anne Whyte\textsuperscript{b}, Bridget Waller\textsuperscript{a}

\textsuperscript{a}Department of Psychology, Glasgow Caledonian University, Glasgow, G4 0BA, UK
\textsuperscript{b}Department of Psychology, John Moores University, Liverpool, UK

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 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 amputee’s 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 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 feedback of a virtual leg that modifies the experience of a phantom leg.
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 sagittal 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
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.

References


Table 1

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

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