Vision Based Games for Upper-Limb Stroke Rehabilitation

J. W. Burke¹, P. J. Morrow¹, M. D. J. McNeill¹, S. M. McDonough², D. K. Charles¹

¹ School of Computing and Information Engineering, Faculty of Computing and Engineering,
² School of Health Sciences, Faculty of Life and Health Sciences,
University of Ulster, Northern Ireland

{burke-j5, pj.morrow, mdj.mcneill, s.mcdonough, dk.charles}@ulster.ac.uk

Abstract

Recent studies have shown the potential benefits of applying technology to stroke rehabilitation. Traditional rehabilitation tasks are often mundane, and can lead to a lack of patient motivation, resulting in little or no independent patient exercise taking place. We describe a low-cost visual tracking system suitable for upper limb stroke rehabilitation in the home which does not require expensive or special equipment and which can be operated entirely independently by the patient. We look at past applications of imaging to stroke rehabilitation, and also game design theory and how it can be applied to stroke rehabilitation. We then describe two small prototype games which implement colour/object segmentation and motion detection to form the basis of our home rehabilitation system.

1. Background

1.1 Stroke

Stroke is the number one cause of severe physical disability in the UK, with over 250,000 people living with disabilities as the result of a stroke [1]. Impairments which stroke victims may suffer include loss of balance, attention and concentration deficiencies, pain, and weakness and paralysis, usually on one side of the body. Such physical impairments can cause patients to lose independence, as they are unable to perform activities required for daily living [2]. Rehabilitation therapy aims to restore a patient’s ability to independently perform these tasks by carrying out exercises on a regular basis. Research has shown that intensive therapy which is conducted early and incorporates physical tasks in an enriched environment, results in more positive outcomes for upper limb stroke rehabilitation [3]. Perhaps the biggest issue with traditional therapy is the mundane nature of the exercises, which can lead to a lack of patient motivation, resulting in only a small percentage of time each day spent doing physical activity, with little independent exercise taking place [4] and reduced patient motivation [5].

1.2 Technology for rehabilitation

Literature has shown that recent developments in technology have potential benefits to rehabilitation therapy [6]. Specifically with post-stroke rehabilitation, a large range of applications have been developed using technologies such as virtual reality [7] and image processor systems [8-10]. The use of programmable systems allows more interesting rehabilitation tasks to be created (in comparison to traditional rehabilitation tasks). This can encourage greater levels of motivation, immersion and involvement leading to a greater sense of presence, which has a consistent positive correlation with task performance [11]. There has been a growing interest in the use of game-like tasks for rehabilitation – games can promote a high level of engagement from the user and this may lead to improved outcome [6].

The application of computer technology facilitates rehabilitation by engaging users in a safe training environment where programmable tasks can be tailored to personal abilities and requirements, helping to motivate the patient and create a more enjoyable personalised experience, leading to improved results [6]. If the exercise can be performed in the patient’s home, this promotes independent exercise which can augment rehabilitation carried out within the clinic. Patient performance data (success/failure rate, type and number of tasks attempted etc) can easily be recorded and uploaded to a remote clinical site, where it can be monitored and analysed by a therapist [12]. However, the high cost and specialised nature of the equipment (such as virtual reality technology) used in many
rehabilitation systems is often a barrier to enabling home-based rehabilitation.

Low-cost, off-the-shelf PC-based webcams may offer an opportunity for affordable rehabilitation systems suitable for deployment in the home. By integrating image processing algorithms for object segmentation and motion detection with game design theory, we aim to produce such a low-cost system comprising a number of configurable game-like tasks suitable for home rehabilitation.

### 1.3 Imaging based systems

Video capture has been implemented in previous studies for post-stroke rehabilitation. Tao et al. [8] proposed a colour based tracking algorithm designed for tracking simple and slow motion for home rehabilitation. Different coloured markers are attached to joints of interest on the subject’s limb (for example, shoulder, elbow and wrist on the arm), assuming that the subject does not wear clothes of a similar colour to the markers. These belts are then tracked in the HSV colour space. An experiment was carried out implementing the algorithm, whilst simultaneously tracking with a commercial marker-based tracking system, Qualisys, for comparison purposes. The experiment showed the algorithm gave promising tracking results and to be suitable for rehabilitation. However, any applications or games for rehabilitation using this algorithm have yet to be shown.

Commercial off-the-shelf video capture platforms have also been applied to stroke rehabilitation. Rand et al. [9] assessed the potential application of the Sony EyeToy to rehabilitation, in comparison to the VividGroup’s Mandala Gesture Extreme (GX). The VividGroup GX is a commercially available platform which uses a chroma key backdrop and a single camera for vision-based tracking, and includes a number of small games. Users view their own image on a large screen, with their background replaced by that of a virtual environment, increasing immersion in comparison to being represented in the software as a virtual avatar. In addition, the user is not required to wear any special devices which may restrict freedom of movement or cause side effects, such as a head mounted display unit (HMD) [13]. The system has been adapted for rehabilitation in several other studies [10, 13], as well as a newer version of the GX known as the IREX (Interactive Rehabilitation EXercise) platform which allows for difficulty scaling and performance recording [14]. The high cost of the GX system, however, has prohibited it from becoming widely used in clinics. Sony’s EyeToy is a low-cost off-the-shelf camera peripheral for use with the Playstation 2 gaming console platform. It can be used on a standard television without the need for a chroma key backdrop or specialised lighting conditions. Numerous games have been developed for the device, such as the EyeToy Play suite, which contains several motion-based mini-games. The results of the study showed that whilst the patients found the EyeToy games enjoyable, some patients, particularly those with acute stroke, expressed frustration as they were unable to complete some tasks with their weaker hand. The inability to scale the difficulty to a patient’s abilities and requirements is clearly a limitation of the EyeToy platform, despite its promising potential for home rehabilitation [9].

Clearly there is potential for an imaging solution to rehabilitation although as indicated above off-the-shelf systems are not always suitable for users recovering from acute stroke. Our group is therefore investigating using imaging with a number of programmable tasks which have been designed specifically for stroke users. Before we present our prototypes we discuss the rationale for incorporating principles from the theory of game design in our rehabilitation tasks.

### 1.4 Game design theory

Salen and Zimmerman define a main focus of game design as “designing game play, conceiving and designing rules and structures that result in an experience for players” [15]. By this definition, game design is centred on the player and focused on maximising the enjoyment that the player gets from playing the game. They also state a goal of successful game design is to create play which is meaningful. Meaningful play relates to the series of choices which the player makes and the outcomes of these choices.

Csikszentmihalyi and Csikszentmihalyi’s theory of flow [16] suggests that challenge should be presented at a steady rate, without slowing to cause boredom, nor increasing beyond player ability. Adaptivity can be used so that task difficulty is altered in accordance with a patient’s progress and ability, so as to continue to challenge the patient at a level which is neither too frustrating nor too trivial, maintaining patient enjoyment and therefore increasing patient motivation [17]. The repetitive nature of physical rehabilitation emphasises the importance of this theory even more so in this context [7].

Rizzo and Kim suggest that “designers of rehabilitation tasks can benefit from examining the formulas that commercial game developers use in the creation of interactive computer games” [6]. These game design “formulas” can be used to help maximise engagement in a task, which can lead to more positive rehabilitation outcomes [11]. Goude et al. [18] proposed a model which mapped game design patterns
to a taxonomy of tasks for stroke rehabilitation, including muscle weakness, coordination problems and constraint induced therapy.

Games offer the potential to engage a patient to the point where they no longer focus on the fact they are in a rehabilitation session [6]. Studies have shown gaming features enhance motivation amongst physical therapy patients [19]. Performance feedback is also important in facilitating the patient learning process in rehabilitation [6]. Feedback can take both auditory and visual forms, and can be used to signify correct or incorrect actions or responses. Gratifying messages or sounds can be presented when a task is successfully completed, leading to an increase in motivation [12]. Without a quantifiable advantage for completing a task in a game, the brain will discard it [20], and therefore it is important that incentive is provided for accomplishment.

Many of the rehabilitation systems reported in the literature encompass tasks which although they are game-like, with animation and graphics, take little account of game design patterns. We believe these provide a sound basis for game development for rehabilitation and have developed two prototype systems incorporating these principles.

### 2. Design

We are primarily concerned with upper limb stroke rehabilitation and our prototype games aim to exercise a patient’s affected arm(s) using reach movements. The patient controls the games by one of a number of interaction mechanisms. Patients can wear a coloured glove or, in the case of severe impairment, may simply hold a soft ball or similar object of a single colour. For some patients even holding such objects may be difficult, so in these instances a piece of coloured cloth may simply be secured to the patient’s hand. We will refer to this coloured artefact as the marker throughout the remainder of this paper. We use a standard low-cost webcam and have developed associated imaging software to track the motion of this marker by its colour in 2D space; we assume that the patient is not wearing clothes of a similar colour to the marker. Gonzalez et al. [21] state that colour segmentation is generally more effective when using the RGB colour model and so we use this colour space for our prototypes. As previously stated, at the start of the game the patient is presented with a small square area on the screen for calibration (Figure 1). The patient should then hold the marker so that it covers the square on the displayed image. This calibration area is deliberately small so that it is easy for the user to perform the calibration task. A short timer counts down in order to indicate when the actual calibration will take place and also to allow time for the patient to prepare.

The colour data from the pixels within the calibration square are plotted into 3D space. The mean colour vector $\mu$ for the calibration area is then calculated, with RGB components of $\mu_r$, $\mu_g$ and $\mu_b$ respectively. The standard deviation for each component, ($\sigma_r$, $\sigma_g$, $\sigma_b$) is also computed.
Once the game is running, the pixels in each video frame which lie within the desired range are identified. For computational efficiency, we just check if a pixel’s colour is contained within a cuboid centred on the mean vector $\mu$. The extent of the cuboid is determined by $(\sigma_r, \sigma_g, \sigma_b)$, scaled by a threshold value $t$. In order to then identify which pixels in the video capture are within the desired colour range, the components of each pixel $p = (p_r, p_g, p_b)$, are checked as shown in the following equations:

\begin{align*}
\mu - t\sigma_r &\leq p_r \leq \mu + t\sigma_r \\
\mu - t\sigma_g &\leq p_g \leq \mu + t\sigma_g \\
\mu - t\sigma_b &\leq p_b \leq \mu + t\sigma_b
\end{align*}

If the pixel satisfies all 3 of these equations, it is segmented as being the same colour as the marker, and therefore it is assumed that the pixel represents a part of the marker. The threshold value $t$ is configured dynamically during the calibration to take account of varying lighting conditions and backdrops.

Motion detection is also implemented in order to help exclude static colours in the background from being identified during segmentation.

### 3. Implementation

Both games were prototyped in the Microsoft XNA programming environment, built on C# and the .NET Framework, and used a DirectShow library for video capture from a webcam. The XNA platform is designed to allow cross-compatibility with Microsoft’s Xbox 360 console. However, due to the need for the DirectShow library which is not yet supported on the Xbox 360 and the lack of native access to the Xbox 360’s own Live Vision camera peripheral, these games only currently run on a PC. In the future, however, there may be an opportunity to port these games easily to the Xbox 360 console if a native video library is provided by Microsoft, which presents another opportunity for deployment in the home as these consoles are typically cheaper than a PC (as well as being easier to maintain). Game console systems offer standardised hardware specifications, avoiding compatibility issues which may be encountered with different PCs.

The games were tested on two different PC webcams of varying resolutions (160x120 and 640x480) with no significant variance in performance.

#### 3.1 Rabbit Chase

The first prototype (“Rabbit Chase”) is controlled by single arm movement (Figure 2). In this game 4 circles (representing holes) are placed in the formation of a square on the screen. The camera’s capture stream is presented semi-transparently on the screen so that the patient can see themselves. A rabbit runs between the four holes, with its next hole being chosen at random. As the rabbit runs between holes it appears transparent, so that it can still be seen but is represented as being underground. In order to score a point, the patient must touch the rabbit when it peers out of each hole, a similar concept to that of a whack-a-mole game. The game detects where the marker is, and if it is at the same hole as the rabbit, the player scores a point. Feedback to the player is via both a buzzing sound and by updating a score counter on the screen. The rabbit sprite also turns a black colour until it begins its run to the next hole, which happens after a variable number of seconds. The aim of the game is to score as many points as possible within the specified time limit. The time limit is displayed at the top of the screen, both in a plain text format with the number of seconds left and in the format of a colour bar decreasing in size. The game’s time limit can be adjusted when creating a patient profile to suit varying levels of ability (see 3.3).

#### 3.2 Arrow Attack

The second prototype Arrow Attack (Figure 3) was developed for bilateral rehabilitation training (using both arms). This game is controlled using two different coloured markers. Again we assume that the colours of each of these markers are unique and not replicated on the patient’s clothing. In this game, four squares are placed in a diamond formation. Two arrows, one pointing left and one pointing right (to signify which arm to use), move between the squares on the screen at a steady speed (specified in the profile). The arrows remain in the box for a short time (again, configurable) before moving on to the next box, which is chosen at random. Each arrow is coloured with the average colour of the respective marker. Scoring in the game is similar to the Rabbit Chase game – during the time that an arrow is in a box, the patient’s marker for that respective arrow should touch the box, with the aim of...
achieving as many points as possible within the time limit. The game has a similar interface appearance to *Rabbit Chase*, with the time remaining and the player’s current score being displayed in the same format.

![Rabbit Chase](image)

**Figure 2: Rabbit Chase**

![Arrow Attack](image)

**Figure 3: Arrow Attack**

### 3.3 Patient Profiles

Prior to commencement, the patient either creates a new profile by entering their name, or selects a stored profile from a drop down box (Figure 4). This profile contains data about the patient, including their previous scores (if available) and the date and time that each score was achieved, allowing a graphical representation of the patient’s progress over time at the end of each session (Figure 5). Other profile data includes the speed and length (in seconds) of each game. The speed of the game determines how quickly the rabbit (*Rabbit Chase*) or arrows (*Arrow Attack*) move between each target and also how long they remain at each target before moving to the next (a slower game speed results in the rabbit or arrow staying at each target for longer). Initially the speed can be chosen according to a patient’s abilities as assessed by a physiotherapist as in standard practice.

There is also an option for the speed to change according to the patient’s progress within a single game: as the patient gains successive hits or successive misses, the game speed increases or decreases respectively. This adaptivity is optional so that players can choose whether or not to have this feature.

![Patient profile selection](image)

**Figure 4: Patient profile selection**

![Patient progress chart](image)

**Figure 5: Patient progress chart**

### 3.4 Game Design Elements

These prototypes provide basic satisfaction of the elements emphasised in Section 2. The *level of difficulty* can be adjusted for the patient’s profile prior to commencing the game, by choosing the speed at which it will run. This allows the patient to find a suitable level with which they are comfortable and gradually increase the level as they progress. The games include a set *time limit* which can be adjusted for each patient’s profile/abilities and *direct feedback* is given directly after scoring a point, both in auditory and visual form, as well as a graphical representation of the patient’s progress after each game. Finally, *precise manoeuvring* occurs by encouraging the patient to make appropriate range movements with their arms, in order to score a point. If the patient does not reach to the target on time, or with the wrong marker, a point is not awarded.

### 4. Conclusions and Future Work

The current colour segmentation processing method is not without issues, as certain colours of objects may be too close to skin colour and may cause conflicts. Implementation of other colour spaces, as well as the evaluation of varying lighting conditions may improve the robustness of the system to changes in illumination. Incorporating more sophisticated methods for motion detection may also improve the accuracy of the game. Outlier removal methods during calibration and the addition of morphological operations may further enhance the system’s performance. Clearly many of these issues can only be addressed with suitable evaluation of the system with stroke users in a variety of home environments. We plan to evaluate the system with stroke patients in the near future.

The system may also be extended to make use of two (stereo) webcams for three dimensional tracking, allowing depth to be tracked as well as the two dimensions tracked in our current system.

In conclusion, the system described offers a low-cost accessible vision tracking system for upper limb
stroke rehabilitation in the home. The tasks incorporate colour segmentation and motion detection as well as game design principles to ensure good patient motivation and engagement. The system does not require any special equipment (other than a standard PC/webcam), can be operated with a variety of different objects (providing they are of a single unique colour) and can be used in most ambient lighting conditions. The system is designed to encourage range movement in a patient’s arm(s) and profiles can be created allowing performance tracking over time.

5. References