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A Rhythm-Based Game for Stroke Rehabilitation

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ABSTRACT

This paper describes the design and development of rhythm-based music game technology to support upper arm rehabilitation following a stroke. The potential benefit of game technology for patient rehabilitation is well established. However, there is a significant gap in research incorporating research into Rhythmic Auditory Cueing (RAC), the practice of synchronising rehabilitation movements with a periodic rhythm. This paper describes the design and development of a prototype game system which incorporates RAC, using music as the rhythmic stimulus. The system can cater for a range of impairments and provide metrics to monitor user performance and progress. The design and operation of the game system algorithms are discussed in detail, focusing on issues surrounding player interaction, rhythm synchronisation and the performance metrics gathered during game play.

1 Introduction

Maintaining motivation throughout a rehabilitation program is essential for recovery after stroke. Up to 80% of stroke survivors are left with upper limb impairment, which can dramatically affect quality of life [1]. Research shows that rehabilitation should be early and intensive, with much of recovery occurring within the first three months [2]. However, the increasing demands upon NHS resources [3] and a shift to move care into community settings [4] often places the burden upon the patient to continue their rehabilitation at home. This may lead to a lack of motivation, resulting in a failure to comply with the prescribed exercise programme. When these factors are considered, there is a need to develop home-based interventions which motivate and engage the stroke survivor, promoting self-management of their rehabilitation.

Game technology has become a focus for many researchers in this area [5]. A well-designed game can motivate and entertain the user through goal-oriented activity, keeping them engaged for prolonged periods of time [6]. However, a game designed for rehabilitation must satisfy clinical needs in addition to providing entertainment [7]. Recent developments in game technology allow for sophisticated game mechanics and the integration of three-dimensional motion capture cameras [8], omitting the need for controller devices which some stroke survivors may find difficult to grasp [9]. Through such interfaces, meaningful, quantitative outcome measures can be obtained which can be used to monitor user performance and progress.

There is a significant gap in research in this area, with relatively little exploration of the potential of rhythm and music-based games. Specifically, there is potential for incorporating research into Rhythmic Auditory Cueing (RAC), the practice of synchronising rehabilitation movements with a periodic rhythm [10]. Although relatively unexplored within a computer game context, RAC has been shown to be effective for upper limb rehabilitation in clinical settings, enhancing smoothness of motion in the paretic arm movements of stroke patients [11] [12] [13] [14].

The nature of the rhythmic stimulus used for RAC warrants further investigation. Notably, [15] developed a prototype games system which incorporated RAC, using user selected music as the rhythmic stimuli. Research indicates that preferred music (music for which an individual expresses a particular preference) may provide therapeutic benefits in a range of clinical settings. When trailed in stroke rehabilitation, [16] reported that exposure to participant selected music can have relaxing effects and improve mood in stroke survivors. Additionally, music has also been shown to change perception of time [17], increase athletic performance [18], and increase engagement during computer gameplay [19].

By combing the factors outlined above, this paper discusses the development of a prototype computer game for upper limb rehabilitation which incorporates Rhythmic Auditory Cueing, using user selected music as the rhythmic stimulus. Key challenges include: the accurate tracking of body movement whilst avoiding cumbersome sensors or controllers which the stroke survivor may find difficult to use; measuring synchronisation between music rhythm and player arm movement; the need to consider an individual's specific impairments, and ensuring that the required range and speed of movement is appropriate and safe for them to engage with.

2 Method

The prototype system requires users to interact with the game through a motion capture camera, tracking skeletal positions in three dimensions. The result of the hemiparesis following stroke can result in an inability to grasp objects with the paretic hand. Therefore, to eliminate the need to grasp a controller device the user interacts with the system through a motion capture camera. For prototyping, the Microsoft Kinect V2 camera [20] has been utilised due to its readily available SDK, previous utilisation as a physiotherapy tool [21] and supporting examination of its suitability for assessment of posture [22] [23].

To drive gameplay, temporal information is extracted from user-selected music. Several algorithms were developed to run during game play and manage rhythm and movement synchronisation, and collect spatiotemporal information used for later analysis. The system can adapt to a user's range of movement, and monitor reach and shoulder position to gauge whether movements are 'correct' or in need of improvement. Additionally, a calibration algorithm assesses the user's natural rate of motion and selects appropriate music, matching musical tempo to motor function.

2.1 User Input and movement

In RAC treatments, patients must move their hand repeatedly between two locations. In the prototype game, on-screen 'targets' are generated as synchronisation points. The graphics, task and means of interaction must remain as simple as possible to allow those with visual impairments to clearly understand the task presented to them and prevent cognitive overload [24]. Arranging targets in a circular, 'clock-face' arrangement, as used in [15] provides a suitable initial framework for the system prototype. Upon loading the game, the user is presented with the targets (see figure 1). The user must move their hand between target points, in time with the rhythm of their chosen music. The destination target is highlighted in green and the ‘next’ destination is indicated with a connecting red line. Movements alternate between the central target and a randomly chosen outer target.

Figure 1 here

2.2 Extracting Temporal Information

As gameplay is driven by user selected music, the initial stage of operation is the extraction of temporal information from an audio file. Due to the high performance observed at MIREX [25], the algorithm developed by [26] is used to extract beat times. The algorithm incorporates audio pre-processing, a Recurrent Neural Network and a Dynamic Bayesian Network which infers beat and downbeat positions. The algorithm outputs a text file which lists the time locations of all beat positions within the audio file. This file is imported into the game engine for further processing.

2.3 Delta and Mean Time

The beat detection algorithm [26] outputs the time locations of each beat. However, the in-game timing system is built around delta time, the time between successive beats. Delta time is useful for in game synchronisation as it is beneficial to know the time until a game event should occur. Additionally, the core principle of the synchronisation algorithm (discussed in section 2.7) is to execute a game event after a given amount of delta time has elapsed. As each delta value gives the time between each beat, the summation of successive delta values provides a longer timeframe - utilising this longer timeframe to trigger game events slows the rate of game play. Therefore, if a variety of delta intervals are calculated for each piece of music loaded into the system, different rates of game play can be achieved for a single piece of music. This flexibility in game play rate is crucial, as the motor impairments experienced by stroke survivors can inhibit the rate at which they can move.

From the text file containing the time locations of all beat points in the audio, an in-game algorithm calculates the delta time of all one, two and four beat intervals and stores each in an array. From this, the mean delta time of each array is calculated, producing values which are used later for user calibration.

2.4 Calibration and Music Selection

Once all timing calculations have been made, the system is calibrated around the user’s motor function limitations, as user safety and clinical effectiveness is crucial. In addition, the tempo of the rhythmic stimulus requires careful consideration - setting a pace deemed comfortable for the patient [27] [28] [11]. As user selected music is used to drive game play, which in turn drives the movement of the user, each piece of music must be assessed for suitability before being allowed to control the rate of game activity. Therefore, it is essential that the calibration stage examines the user’s rate of movement and finds the best fit music and beat division.

To perform this assessment, the user's natural rate of movement must first be established. To obtain this measurement, the mean movement time between two points must be calculated. However, as each user's motor function may limit their range of reach to different extents, an appropriate travel distance must also be established to avoid potentially unsafe activity. So the calibration stage consists of the following steps:

1. Assess movement range

2. Assess movement rate

3. Select best fit music at appropriate beat division.

The first stage of calibration assesses the 'screen reach' - the safe range of X-Y reach for that particular user. The user is tasked with moving their hand to the left of the screen to a comfortable reach point, then right, top and finally bottom. At each point, the co-ordinates are stored, and from these values, a 'safe play area' is established which all subsequent game activity must be located within.

Using the X reach as a spacing measurement, two targets are automatically generated to the left and right of the screen. The user is then tasked with moving between these two points at a rate they find comfortable, the system logging the arrival time at each target. After 10 cycles between targets, the mean travel time between targets is calculated. As the final gameplay task involves reaching from an inner target to an outer target (half the user's total screen reach, therefore half the total movement time) the mean movement time is divided by two. This value is then compared to the series of mean delta times from each music track (1, 2, and 4 beat mean deltas). The closest match and corresponding music are located, then the relevant delta array is selected to drive gameplay through the synchronisation algorithm (section 2.7).

2.5 Arm Extension and Flexion Calibration

An additional calibration stage is incorporated to account for depth, monitoring user arm extension in three dimensions and observing posture for undesired deviations in shoulder position. When considering posture or movement, the absolute position of a single joint is only relevant when its relative position to surrounding joints is taken into consideration. Therefore, 'correct' movement and posture can be considered the appropriate relative positioning of joints. Another algorithm was developed to monitor relative hand and shoulder position, distance and travel direction. The system detects when a user's arm is moving in a state of extension or flexion and when full extension and flexion is reached. Additionally, if the user compensates by leaning with their upper body rather than fully extend their arm when reaching (a common behaviour in stroke survivors), the algorithm alerts the user to extend their arm fully and keep their shoulder stationary.

2.6 Target Generation

To create the game play environment, a series of targets are procedurally generated. The number of targets can be chosen to simplify the task or add complexity if required. To ensure user safety, the targets are distributed within boundaries set by the output from the screen reach algorithm. Using these values, the system generates a series of targets arranged in a circle around a central target as seen in figure 1. Once all targets have been generated, the game enters a state of 'waiting'. When the user is ready to play, the game is activated and controlled through the synchronisation algorithm.

2.7 Synchronisation Algorithm

An in-game algorithm was developed to provide accurate synchronisation between audio and gameplay. Audio to gameplay synchronisation is extremely important as the user must feel an explicit link between music and game activity. The algorithm continuously compares the accumulation of delta time to a timer which runs in synchronicity with the current audio (the game music). Once a given amount of delta time has elapsed, an execute command is sent to trigger game activity in time with the beat of the music.

The calibration algorithm described in section 2.4 locates the best fit beat delta array and corresponding music. This array of delta times is taken as input to the synchronisation algorithm and provides all timing values used for audio-video synchronisation.

After the user signifies the game to start, the game music begins, and a timer initialises in synchronicity. A conditional test is performed on each frame of game play which assess if the time since the game music began is greater than or equal to the first value of the selected beat delta array. If found to be true, an execute triggers a gameplay event which coincides with the beat of the music. At this point, the next delta value is added to the previous, creating a running total of delta times. As the timer advances, the conditional test is continuously performed, now assessing if the timer is greater or equal to the running total of delta time. If found to be true, a further execute is sent and the next delta value is added to the running total, creating a new value for comparison. This process continues until all index points within the selected delta array have been used, which signifies the end of the audio file and concludes gameplay. This process is described in figure 2.

Figure 2 here

As algorithm performs the conditional test on each frame of game play, computers which can produce higher framerates will perform the test more frequently. However, this method of operation dictates that the comparison and subsequent execution is performed as fast as the computer can do so, eliminating the possibility of 'missed beats' if an attempt was made to synchronise game events and music at a precise time point, which slower systems may not be able to achieve. The total timing error of the algorithm is therefore dependent upon the game's frame rate. However, regardless of frame rate, the algorithm operates such that video will always precede audio, which is the preferred method of audio-video synchronisation [29]. Various organisations within the broadcast industry have insisted upon specific positive and negative boundaries of error for synchronisation. [30] summarised the standards implemented by several bodies, shown in table 1.

Table 1 here

Combining these standards, the mean acceptable threshold for delayed audio can be taken at 58.75ms. Table 2 shows the approximate timing error of the synchronisation algorithm at a variety of frame rates. Notably, even at extremely low frame rates the timing error is below the threshold.

Table 2 here

3 Output and Analysis

To assess user performance, data can be collected from the system and analysed. The system can output spatiotemporal information from any of the 26 joint positions from the Kinect camera. When the positional data is collected within the game engine it is converged with a time stamp which describes the timing of the music. This data highlights movement and position of each joint, and its relationship to the timing of the music. The collected data can be analysed to measure several factors, such as synchronisation to rhythm, trajectory, position, velocity and acceleration.

3.1 Position and Trajectory

Positional information can be exported from the game engine and plotted with beat times overlaid to indicate synchronisation with beat points. Figure 3 shows the X and Y trajectory of the left hand of an individual over 10 seconds of play. Three targets were generated along the X axis, the user cycling between each target on loop. Note this data was collected from a healthy user performing a short test at 117bpm. For those who experience paresis following stroke, the trajectory would likely show greater inconsistency.

Figure 3 here

3.2 Velocity and Acceleration

Using the beat times as segmentation points, the movement data is split to give insight into the movement between beats. The resulting data can be used to calculate factors such as velocity and acceleration, which can indicate the consistency of a user's movement. By layering consecutive sections and taking the average, velocity and acceleration can be observed over a given time frame. Figure 4 shows the average velocity of a healthy individual over 20 seconds of gameplay.

Figure 4 here

4 Conclusion

The prototype rhythm game described in this paper aims to capitalise on the potential benefits of rhythmic auditory cueing in a game play context, and provide therapeutic benefits by using music as the rhythmic stimuli. Key challenges centre around player movement tracking and synchronisation with music rhythm, toward which several algorithms have been developed and described in this paper. Although in prototype stage, preliminary evaluation of data demonstrates the potential of the fully developed system to act as a powerful analytical tool. Output such as average movement rate, movement range, arm extension, trajectory, velocity and acceleration provide quantitative metrics which give insight into a user's performance. Such data can be collected and analysed by a health professional over successive sessions to assess if motor function is improved through repeated engagement.

Future work will further integrate rhythmic synchronisation into the game activity, with the aim of creating entertaining and engaging games for the user. Consultation with medical professionals will guide further system development, to ensure the system's data output is relevant and useful. Additionally, the posture and movement monitoring algorithm which currently covers arm extension, flexion and shoulder position will be expanded to provide full upper limb monitoring in real time.

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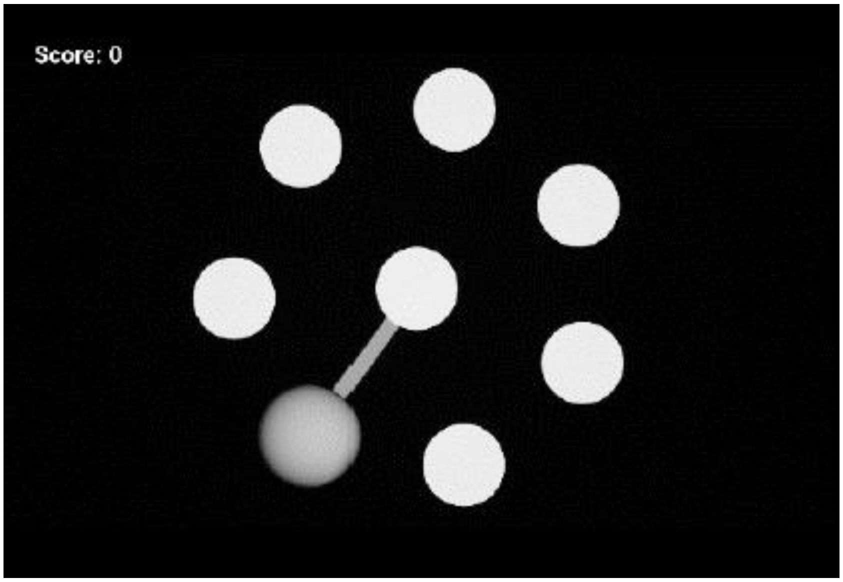

Figure 1. The target game

```
▷ Input array of beat delta times
procedure DeltaTimer(BeatDeltaArray)
▷ Initialise timer
    Start global timer as GlobalTime
    if GameHasStarted = true then
        Begin Audio Playback
▷ Store timestamp
        AudioStartTime ← GlobalTime
▷ Init delta count
        DeltaCounter ← BeatDeltaArray(i)
▷ Gameplay loop
        for Each frame do
            MusicTimer ← GlobalTime − AudioStartTime
            if MusicTimer ≥ DeltaCounter then
                Trigger Game Event
                BeatDeltaArray ++
                DeltaCounter += BeatDeltaArray(i)
            end if
        end for
    end if
end procedure
```

Figure 2. Synchronisation algorithm

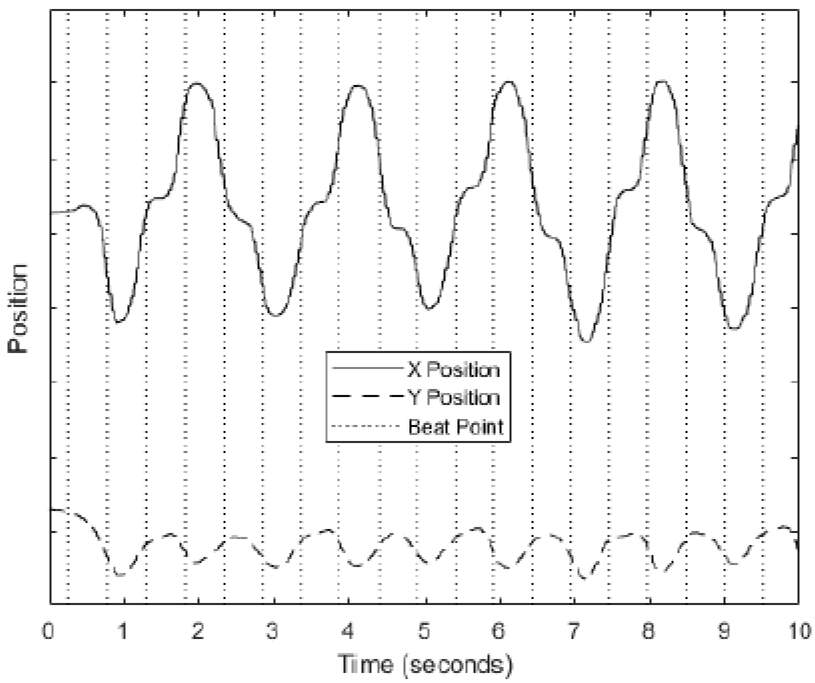

Figure 3. Trajectory with beat times

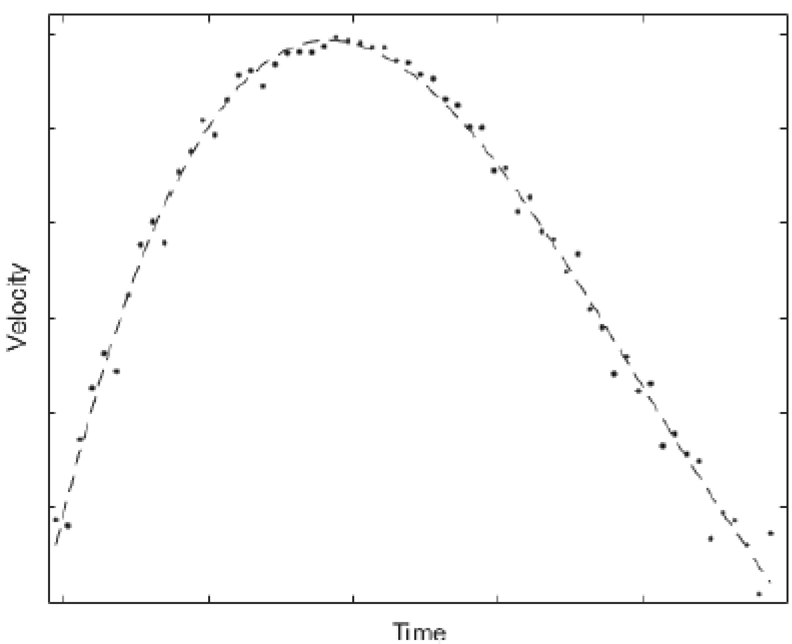

Figure 4. Mean Velocity

Standard	Year	Maximum Difference (milliseconds)	
		Delayed Audio	**Advanced Audio**
ITU-R BT.1359	1998	30	22.5
ATSC IS-191	2003	45	15
EBU R37	2007	60	40
Subjective evaluation by ITU-R, undetectable limits	1998	100	20

Table 1. Audio-video synchronisation limits of different standards [30]

Frame Rate	Error
20 fps	- 50.01ms
60 fps	- 16.67ms
120 fps	- 8.33ms

Table 2. In-game synchronisation error