Glove-Based Technology in Hand Rehabilitation

Jamie Taylor, School of Computing and Intelligent Systems, University of Ulster, Londonderry, Northern Ireland

Kevin Curran, School of Computing and Intelligent Systems, University of Ulster, Londonderry, Northern Ireland

ABSTRACT

Injuries to the hand are more common than those of any other body region and can have considerable financial, time-measured and psychological impact on not only the victim but the community as a whole. Hand rehabilitation aims to return people to their pre-injury roles and occupations and has proved largely successful in doing so with the potential for technology to improve these results further. However, most technology used in hand rehabilitation is based on expensive and non-durable glove-based systems and issues with accuracy are common among those which are not glove-based. The authors outline an accurate, affordable and portable solution wherein the authors use the Leap Motion as a tool for hand rehabilitation. User feedback will be given primarily through an animated 3d hand model as the user performs rehabilitative exercises. Exercise results will be recorded for later viewing by patients and clinicians. The system will also include Gamification aspects, techniques which (while proven to increase participation) have seen little to no use in hand-rehabilitation systems.

Keywords: *Gamification, Pre-injury, Rehabilitation, Technology, User-feedback*

1. INTRODUCTION

The human hand is one of the most complex creations in existence and the main enabler of our modern lifestyles. Given this intense and extensive use, it should come as little surprise that injuries to the hand are more common than those of any other body region (Trybus, et al., 2006). Injuries such as Repetitive Stress Injuries (RSI's), lacerations and crushing are just a few common injuries to hand. Such injuries are treated through hand rehabilitation (Amini, 2011). This includes measures such as splinting the hand and prescribing rehabilitation exercises designed to strengthen the muscles in the hand and prevent build-up of scar tissue which would otherwise affect joint movement. Individuals who find themselves afflicted with these kinds of injuries can experience great emotional and psychological since an injury to our hands can threaten our independence and normality in a way few things can. This process is not only time-consuming and costly for the person injured; in the UK, over £100 million is spent

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every year treating these kinds of injuries (Dias & Garcia-Elias, 2006). Current rehabilitation is largely analogue, with no technological intervention, primarily due to cost. Data gloves, the most common technological rehabilitation aid, can potentially cost thousands of pounds (O'Donnell, 2010). There is a clear need for something accurate, portable and affordable.

At present, it is common for individuals with hand injuries to undergo rehabilitation using no technical aids. Efforts to improve rehabilitation through the use of technology have led to a number of systems being proposed, these systems are most glove-based, with few alternatives. These glove-based systems are (for the most part) prohibitively expensive (O'Donnell, 2010) and the few alternatives such as Kinect (Bond, 2011) can suffer from portability and accuracy issues. It should also be noted that none of these system take advantage of gamification. Gamification is the use of game-like elements in traditionally non-game like settings and has been proven to increase user enjoyment and participation.

This paper outlines the design and development of a software based system for hand rehabilitation using the Leap Motion. The Leap Motion is a recently released motion-based device which has yet to be investigated as a tool for hand rehabilitation. User feedback comes primarily from an animated 3d hand model which will reflect the users hand movements in real-time. The results from the exercises are stored for later viewing by either the patient or a clinician. Furthermore, the project uses gamification elements to better encouraging patients to adhere to prescribed exercise programs.

2. HAND INJURIES

It is estimated that treatment for hand injuries costs the UK approximately £100 million per year. However, this problem spans much farther than the UK; the US for example, spends approximately $18 billion treating upper extremity disorders and Germany spends approximately €2 billion treating severe trauma with a ratio of 25 patients per 100,000 of the population (Dias & Garcia-Elias, 2006). Looking at RSI as a more specific example, we see that RSI alone is estimated to cost UK employers approximately £300 million per year (Strategy One, 2008). This is again mirrored in other parts of the world, with the US spending approximately $20 billion on RSI compensation each year (Yassi, 1997). Of all the hand injuries described above, amputation is deemed the most expensive, replantation of the hand or some part of the hand can cost up to 1.6 times a patient's annual salary. Nerve injuries are the second most expensive injury to treat, costing between €51,238 and €31,186 (Holmberg, et al., 1996). Speaking in more general terms, (Trybus, et al., 2006) calculate the mean cost of a hand injury to be $6126.76 or €4507.29. When discussing the financial impact of hand injuries, it is interesting to note the uneven distribution of direct to indirect cost. An example of a direct cost would be that of a surgical procedure whereas examples of indirect cost would include sick leave and outpatient travel. Direct cost was found to make up only 4% of the total expense whereas indirect costs made up the remaining 96% (Trybus, et al., 2006). The impact of hand injuries is not just measured in terms of financial cost to employers through compensation or lost productivity; we can also use time related metrics such as work days lost or treatment duration in days when measuring the impact of injuries to the hand. Reports indicate that hand injuries account for 27% of all work-related injuries requiring more than 1 day of leave (G, 2003). Given that hand injuries are a world-wide concern, it is realistic to suggest that hand injuries can result in millions of work days being lost, as workers are forced to take leave in order to recover from their injuries. RSI for example costs UK employers approximately 3.5 million working days alone, with each affected person taking an average of 13 days off due to their injury (Strategy One, 2008). Initial, hospital-based treatment of hand injuries can last anywhere between 1 to 86 days with an average of 9.1 ± 9.3 days. Total treatment duration, time in hospital and aftercare can last between 1 to 420 days with an average of 76.9 ± 67.8 days, meaning hand injuries often take longer to treat than injuries to other regions of the body. It should also be noted that the severity of the injury does, as one would expect, affect the duration of treatment (Trybus, et al., 2006). In addition to the financial and time-related impact observed above, hand injuries can also have a severe psychological impact on those afflicted. It is common for people to view themselves in relation to their occupational role, rank and level of ability (Hasselkus, 2002). Injuries that then interfere with one's occupation or daily routine - such as those involving the hands - can cause severe distress and a strong yearning for a return to normalcy (Hasselkus, 2002). Of all the types of hand injuries described here, nerve injuries have the most prolonged and profound psychological impact on the patient, those suffering from a nerve injury in the hand are commonly left with some form of persistent, residual disability that they are forced to contend with for the remainder of their lives. The likelihood of persistent, residual disability after hand injury spans from 1% to 100% with 13.6% of patients being affected on average (Dias & Garcia-Elias, 2006). Psychological issues caused by hand injuries and associated persistent, residual disability includes flashbacks, Post-Traumatic Stress Disorder (PTSD) and concerns with personal appearance (Sousa, et al., 2013).

2.1. Treatment and Rehabilitation of Hand Injuries

This research is focused on the development of a hand rehabilitation system using the Leap Motion; because of this we will be focusing on hand rehabilitation and its use as a treatment for hand injuries to the exclusion of other treatment measures such as surgical procedures. Hand rehabilitation therapy is a form of occupational therapy (Amini, 2011). Hand rehabilitation/therapy is focused on "…*enabling the client to regain functional use of the traumatized arm and hand ... and return to their pre-injury occupations.*" (Case-Smith, 2003). The treatment offered by hand therapy can be divided into two main categories; these are preventative, non-operative and post-operative. Using the information presented in (American Society for Surgery of the Hand, 2011), a more complete list of treatment options offered through hand therapy can be compiled and is presented in Table 1.

Of the treatments listed above, it is "*design and implementation of home exercise programs…*" and "*instruction in home exercise programs*" that are of particular relevance and interest to this project. (Lavanon, 2013) Points out that such hand therapy exercises should be *"motivating, repetitious, interesting, challenging and graded"*, (Amini, 2011) adds that these exercises should incorporate *"usual and customary occupation activities…"*, this is

Table 1. Non-operative/postoperative hand therapy treatments

Preventative, Non-operative, Conservative	Postoperative Rehabilitation
Management of acute or chronic pain	Management of open or sutured wounds
Desensitization following nerve injury or trauma	Control of hypertrophic or hypersensitive scars
Sensory re-education after nerve injury	Reduction of swelling
Design and implementation of home exercise programs to increase motion, dexterity and/or strength	Fabrication of orthoses to protect surgery or increase movement
Training in performance of daily life skills through adapted methods and equipment	Instruction in home exercise program
Splint fabrication for prevention or correction of injury	
Conditioning prior to returning to work	

important, given that the aim of hand therapy as described above is to return patients to their occupational and pre-injury roles. At present, it is common for home exercise programs to be performed without the use of technological aids or systems. Hand therapy offers a high success rate as a treatment for hand injuries. Of those studied and treated in (Case-Smith, 2003), 80% returned to work after an 8 week course of treatment consisting of – on average – 13 hours of treatment. These results are of particular relevance because during this time, the occupational therapist was the patient's sole provider of rehabilitation services, showing that hand rehabilitation/therapy even in isolation can be greatly successful and beneficial.

While hand therapy is already a successful form of treatment for hand injuries (Case-Smith, 2003), there is evidence to suggest that this form of treatment could be improved further through the use of technology (Lavanon, 2013). Argues "*...advanced technology can enrich treatment and help patients...*" looking in more detail, we see that technology can be applied to other areas of hand injury treatment beyond rehabilitation. The CODA system seen in figure 2 for example, can be used as a diagnostic motion analysis tool. More relevant to this project however, is the discussion of technology as a rehabilitative tool, in particular, the use of everyday "off the shelf" technology such as the Leap Motion. An example of such a system is described in (Lavanon, 2013), where a VR system was constructed using the PlayStation EyeToy, a common consumer device. The EyeToy based system was found to be an effective and – more importantly – enjoyable way of exercising, however the system fails to grade exercises. This is something we aim to implement in the proposed system, even enhancing it further through the introduction of gamification elements.

2.2. The use of Glove-Based Technology in Hand Rehabilitation

Glove-based technology, specifically data-glove technology, is arguably the most common form of technological aid in treatment and managing of hand injuries. Therefore we dedicate a section solely to it. Example applications include motor assessment (Lautman, 2012) and as a tool for rehabilitative exercises (O'Donnell, 2010). This high adoption rate is primarily a result of the richness of the information provided by such systems (Dipietro, et al., 2008). To define a glove-based system, we use the definition provided by (Dipietro, et al., 2008), where a glove-based system is defined as *"a system composed of an array of sensors, electronics for data acquisition/processing, power supply and a support for sensors that can be worn on the user's hand."*. Such gloves are typically made of Lycra onto which sensors are sewn, these sensors then record data of the wearer's hand movements, joint movement, fingertip positioning and so forth. We now look at a few glove-based systems that show promise in a hand rehabilitation environment.

The 5DT Data Glove Ultra developed by Fifth Dimension Technologies (Fifth Dimension Technologies, 2011), is a data glove aimed primarily at Motion Capture and Animation Professionals. The gloves has a total of 14 sensors, uses proprietary optical-fibre flexors and supports $2^4 = 16$ possible gestures (Dipietro, et al., 2008). The glove communicates with a computer via USB cable or RS 232 serial port through an additional kit (sold separately); another kit is available to allow for wireless operation via Bluetooth (also sold separately), allowing 8 hours of use on a single battery at a range of up to 20 meters. The glove itself has a base unit price of $995 (£608.79); this includes the glove and the 'GloveManager' proprietary calibration software. The 5DT Data Glove Ultra is available in left and right variants.

The HumanGlove developed by HumanWare (HumanWare, 2010), is a glove-based system developed primarily for use in medicine, rehabilitation, VR and Telerobotics. The glove uses Bluetooth technology by default, emulating an RS 232 port in software and uses a total of 22 hall of effect sensors to measure flexion/extension and abduction/adduction (2 sensors per finger, 2 for the thumb and 2 for the wrist). Like the 5DT described above, the HumanGlove uses proprietary software for calibration, in this case, a package called "Graphical Virtual Hand".

The Peregrine Gaming Glove is a glove-based system developed by Peregrine Canada (Peregrine, n.d.). The glove is designed for use in games where the number of actions available to the player is vast, games such as MMORPGs or MOBAs. The glove has 18 touchpads, 3 activator pads together with stainless steel conductive traces; allowing support for 30 programmable actions configures using the proprietary GloveBox software shown in figure 8. However, the glove cannot sense flexion/extension or abduction/adduction of the fingers or thumb, instead, the glove detects the thumb as it touches one of the 18 touchpads lining the fingers. The main attraction of the Peregrine Gaming Glove from a hand rehabilitation standpoint is the price; the glove has a unit price of $149.95 Canadian (£84.34) which has allowed students to use the glove in numerous rehabilitation system oriented projects (O'Donnell, 2010), (Lautman, 2012).

While glove-based systems offer a wealth of information to developers and researchers, it should be noted that glove-based system suffer from a vast number of flaws. Glove-based systems suffer from robustness and durability issues due to the Lycra fabric, this lack of durability is exacerbated by the price of these systems. Issues of portability when one is tethered to a computer should also be considered (again, the extra cost for wireless options exacerbates this) in addition to the need for constant calibration. The most relevant draw-back of these system from a hand rehabilitation standpoint however, is the simple fact that conditions such as rheumatoid arthritis can leave a patient unable to even wear the glove.

2.3. The use of Non Glove-Based Technology in Hand Rehabilitation

Though glove-based systems have proven extremely popular and effective, they do suffer from drawbacks as we have seen. Issues with pricing, durability and simply being unable to wear the glove due to conditions such as rheumatoid arthritis have generated great need, interest and opportunity for non-glove-based systems.

The Open Source Computer Vision library or OpenCV is an open source computer vision initiative. Started by Intel in the mid to late 90's and released to the public in 2000. The project has since been handed over to Willow Garage and Itseez, ensuring a continuing release schedule. OpenCV contains over 500 C/C++ based functions, allowing for a vast array of computer vision based applications, including medical imaging, security and robotics (Bradski & Kaehler, 2008). The library is compatible with a wide range of commercially available camera equipment, the camera uses the position and colour of a pixel to build up a matrix of numbers, this matrix is then passed to the program. OpenCV has been shown to computationally outperform other computer vision libraries such as LTI and VXL (Bradski & Kaehler, 2008). Furthermore, OpenCV can benefit by as much as 20% from IPP, if they are present in the host system. This makes OpenCV a powerful and accessible library for computer vision. Such a resource would potentially be a good supplement for glove-based systems; however, we do not plan to use such a supplement technology in our Leap Motion-based system.

The Kinect is a gesture control device primarily aimed at gaming applications for the Xbox 360 and later Windows based PCs. However, since its initial release, engineers both professional and hobbyist have used it in a wide array of applications ranging from robot guidance (Ackerman, 2011) to hand rehabilitation shown in figure 11 (Bond, 2011). The Kinect is made up of three main sensors, the first of which is an IR depth-finding camera used to read input in the IR spectrum, the second is an IR transmitter and the third is a standard RGB camera. Both the IR depth-finding camera and the RGB camera run at a resolution of 640x480 with a frame-rate of 30 frames per second. The appeal of the Kinect with regards to hand rehabilitation lies in the fact that it is relatively low priced compared to the glove based systems described above, retailing for approximately £85. This can allow for a high adoption rate among patients, furthermore, the Kinect is not bound by the issue of right VS left handedness, the same unit can be used to train either hand, whereas with glove-based systems, a second glove would have to be ordered. Lastly, the Kinect is much more durable and robust, gloves wear out over time to the point where they must be replaced, which is costly, and a Kinect by comparison may never need to be replaced. While an interesting device, the Kinect does suffer from an array of drawbacks; for example, the device only supports a field of view of 57.8º. However, the main drawback from a hand rehabilitation standpoint is unquestionably its minimum range of 0.6m; there is however third party lenses that try to reduce this with some success (Pc Mag, n.d.).

The Leap Motion, shown in figures 1 & 2, is a recently released (mass shipping began July 2013) motion-based device for computer interaction developed by Leap Motion Inc. (Leap Motion Inc, 2013) who claim the device offers accuracy to within 0.01mm. The device, as shown in figures 1 and 2 is made up of 2 monochromatic IR cameras (the grey dots in figure 2) and 3 infrared LEDs (the red dots in figure 2), giving the device a semi-spherical observational area with a distance of approximately 1 meter. This observational area is smaller than that of the Kinect, which is designed to monitor the entire body; however this allows the Leap Motion to operate at a higher resolution and accuracy where accuracy is defined as *"the ability of a 3D sensor to determine a desired position in 3D space"* (Weichert, et al., 2013). The IR cameras can run at up to 300 frames per second (as opposed to 30 with the Kinect) while the LEDs generate a 3D pattern of dots made up of IR light (Anon., 2013). A study on the accuracy of the Leap Motion found that while the claimed 0.01mm accuracy is not achievable, a high precision accuracy of 0.7mm was (Weichert, et al., 2013) achievable.

This makes the Leap far superior to the standard deviation of 1.5cm (15mm) found in the Kinect. How the Leap Motion views the users hands can be seen in figure 15, where the freely bundled "Leap Motion Visualizer" software is demonstrated. In addition to the technical improvements, the Leap Motion enjoys other benefits over previous systems. Firstly, the Leap Motion is more affordable than any other device discussed here - even the Kinect (£85) - the Leap Motion is currently available for £65. The Leap Motion also benefits from its small size, coming in at 0.5 inches in height, 1.2 inches in width and 3 inches in depth with a weight of only 0.1 pounds (Leap Motion Inc,

Figure 1. Leap motion

2013), making it more portable than any other device discussed here. Another advantage of the Leap Motion (this one it shares with the Kinect) is durability; the Leap Motion is not prone to wear and tear that eventually claims many a glove-based system. It is clear that the Leap Motion is more accurate, more affordable and more portable than anything that has come before it. Due to these advantages, we chose Leap Motion as the means for delivering the system.

2.4. The Role and Potential of Gamification

Gamification can be defined as *"the use of game design elements in non-game contexts"* (Deterding, et al., 2011). Gamification is a fast growing initiative, with the aim of increasing motivation and participation among users of non-game applications and is expected to revolutionise all aspects of life in the not too distant future (Chatfield, 2010), (The Pleasure Revolution: Why Games Will Lead the Way, 2011). One of the first examples of gamification been used in a popular commercial product would be the achievement system used in the Microsoft Xbox360 console (Jakobsson, 2011). The achievement system allows users to complete in-game challenges and accumulate "Gamerscore" as shown in figure 3. Due to its success, the system has since been implemented in numerous other platforms including the Sony PlayStation 3 and the popular PC Steam network. An ideal example of game design elements being used in a non-game context however would be the Khan Academy (Khan Academy, 2013). The Khan Academy is a non-profit organisation with the aim of providing *"a free world-class education for anyone anywhere"*. The site allows users to watch videos on a wide variety of educational topics, complete exercises for which they can build up streaks, earn badges and a Gamerscore-like collection of points in addition to an array of real-time stat tracking tools as seen in figure 4.

More relevant to this project however, is the use of gamification in a medical and rehabilitation setting. (Gerling & Masuch, 2011) Explore the application of gamification in augmenting the lives of frail elderly people who are no longer able to participate in certain real-life activities due to age (such as a recreational walk through a forest). They suggest that if we are able to overcome challenges such as the lack of experience with digital games and systems then elderly users can benefit not only cognitively, physically thanks to increased participation in therapeutic activities, but also socially from the experience, as gamified applications of-

Figure 2. Leap motion schematic view

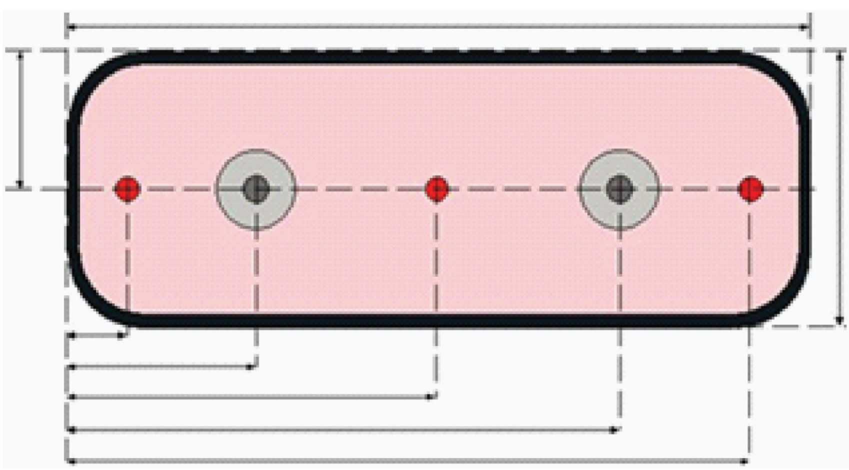


Figure 3. Xbox 360 achievements

fer the opportunity for friendly competition. Gamification and 'gamified applications' such as serious games have been proven to work in medical undertakings such as stroke rehabilitation(Burke, et al., 2009). The authors look at the use of gamified applications in helping those affected by strokes regain control of the affected limbs. Their results show that gamified applications can be used to help solve a common issue experienced by many stroke survivors undergoing therapy. The issue being that the everyday actives assigned to them as part of their rehabilitative therapy are boring and uninteresting. Couple this with the depression

Figure 4. Khan academy stat tracking and achievement system

Figure 5. System architecture

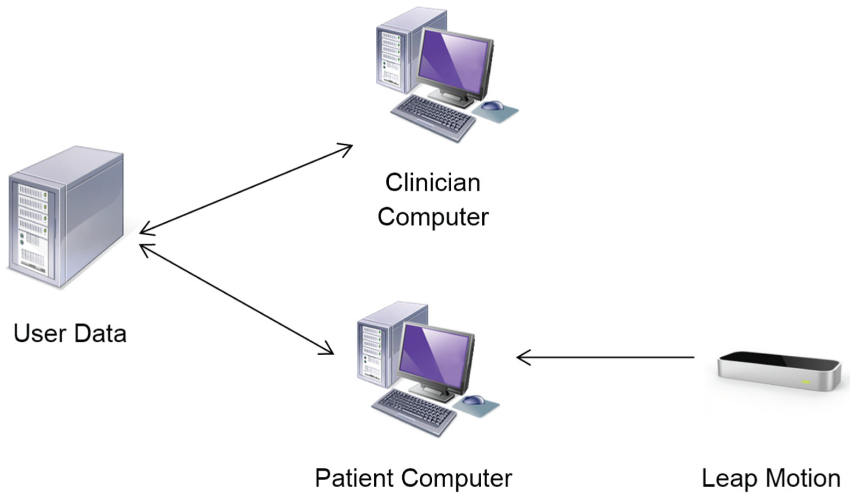
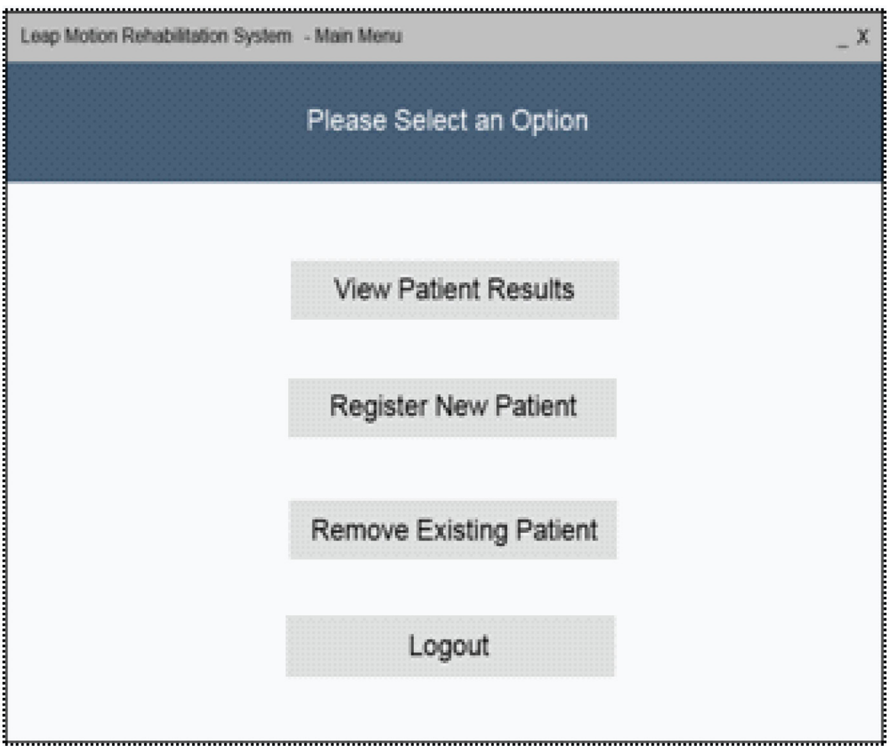


Figure 6. Clinician main menu



that is common among stroke survivors and the result is low user enthusiasm, low participation and poor results in terms of limb functionality regained through therapy. The study proves that gamification can make activities these engaging and stimulating, encouraging user participation and by extension, leading to better results in terms of regained functionality.

The study that is of most relevance to this project however is that conducted in (Jacobs, et al., 2013), where the authors investigate the use of gamified applications in arm-hand training for stroke survivors. Here, a proprietary 'serious game' (a form of gamified application) named CONTRAST was used wherein the user completes task-oriented exercises involving the manipulation of everyday items. Results of the study show increased user participation and by extension, improved arm-hand functionality. They point out that gamified applications make rehabilitative exercises *"meaningful…"*. However, research would suggest that gamification has yet to be used in a hand-rehabilitation setting despite the fact that both hand rehabilitation and gamification place emphasis on identifying the user/patients personal goals *"incorporating usual and customary occupational activities into treatment…"* (Amini, 2011), likewise, making the experience relevant to the user is also an essential part of gamification *"… it is important to catch the user's personal goals…"* (Groh, 2012).

3. SYSTEM DESIGN

A visual layout of the system components and how they fit together is now presented; the diagram includes all the major components of the system (the patient/clinician machine, the Leap Motion and the user data). The patient's machine interacts with the Leap Motion controller and both the patient and the clinician

Figure 7. Patient main menu

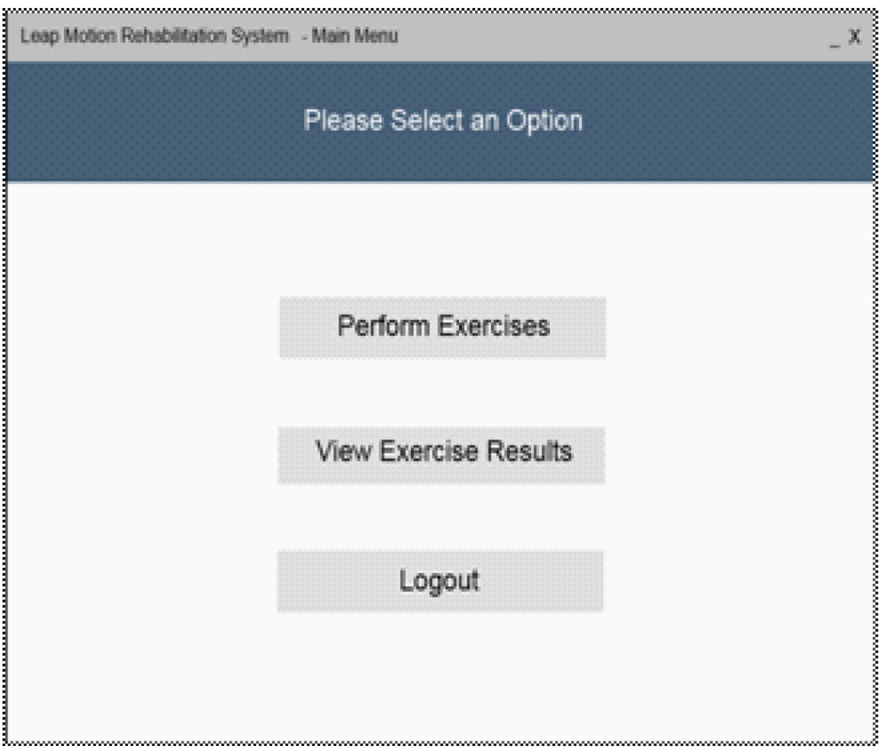
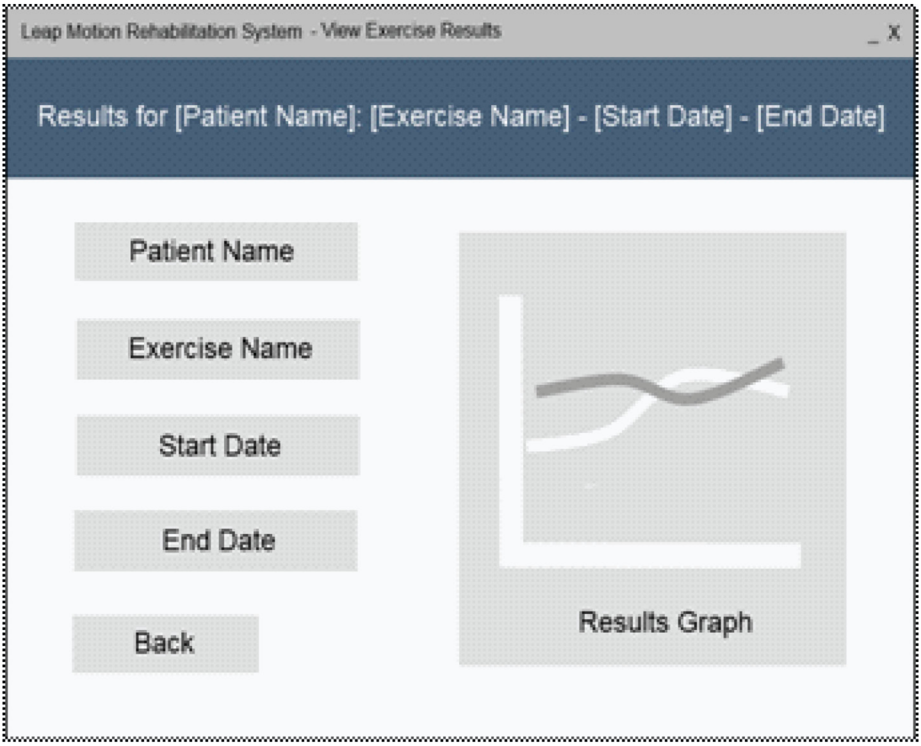


Figure 8. Clinician version



machines interact with the user data (exercise times and results). The most common approach to storing the user data would be in a database of some description.

Figure 6 and figure 7 show the use of calming colours (the blue header) as opposed to colours such as red seen in previous systems (which instil a sense of anger and or panic) along with friendly language (the use of 'please' and avoidance of jargon such as 'credentials').

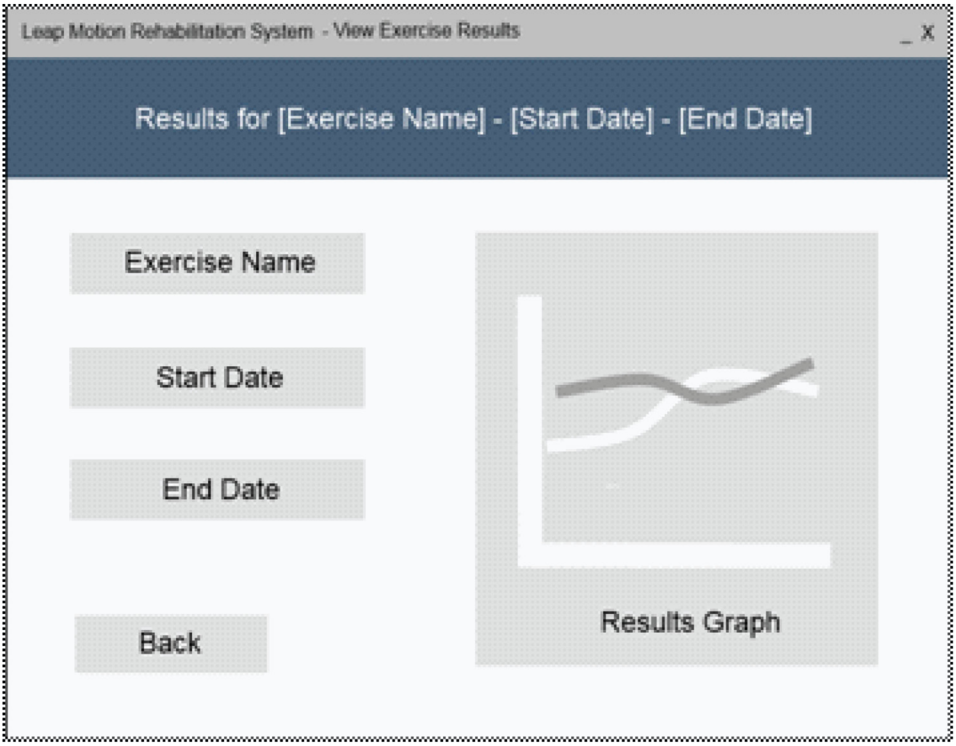
Figure 6 and figure 7 show the main menu for a clinician user; this is where usage paths between clinician and patient users start to diverge. A clinician user has the ability to manage patient accounts (via register and remove) whereas patient users have the option to perform exercises. Both users share the ability to view results and logout.

Figure 8 and Figure 9 demonstrate the view exercise results screen. Here we see with the clinician version in Figure 8 and the patient version in Figure 9. Both versions will allows the user to view results by exercise type as well as being able to specify a timeframe (via start and end dates) for the results. The only variation is the ability of the clinician to view the results of numerous patients, whereas a patient can only view their own results.

Figure 10 shows the exercise screen which is exclusive to patient users. On the left of the screen, a real-time 3D animated hand model will be used to provide real-time feedback to the user. Information such as exercise instructions, repetition count and time taken will be documented on the left of the screen. Possibilities for continuing to the next exercise include a button (as seen in the image), holding ones hand still or possibly leveraging the Leap Motions built in swipe gesture. The back button will be used to return to the main menu.

The main menu screen will not be covered as it is a simple collection of calls to the naviga-

Figure 9. Patient version



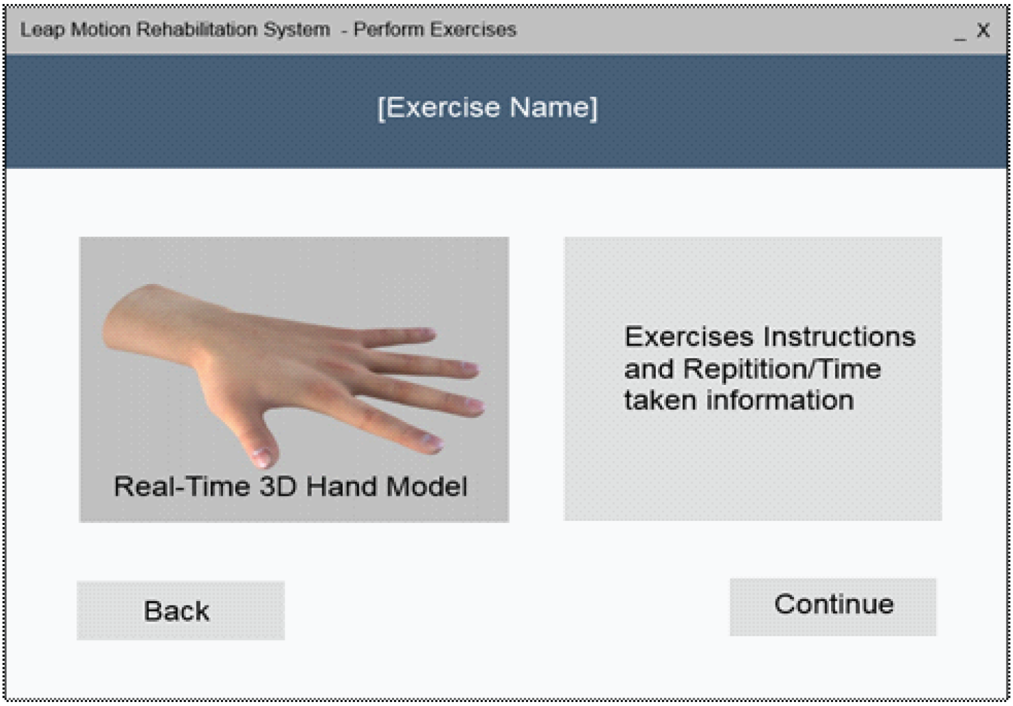
tion system used to load the next screen depending on the user's selection of either performing exercises, viewing results or logging out. We will describe the main focus of the patient side of the system and indeed that of the entire LMRS: the perform exercise functionality. This part of the system pulls together WPF, Leap Motion and XNA to deliver the user experience seen when the animated hand moves during exercises. The calibration is repeated if the user takes their hand away from or goes out of range of the Leap Motion. These key metrics are described below and can also be seen in figure 11.

The magnitude of the vector between the front-most fingertip and the palm. A sizeable change (decrease) indicates that the front-most finger is getting closer to the palm meaning the user has begun to clench their hand into a fist. At this point we start the timer. Exercises 1 and 3 use this logic ($\Delta\|v\| > n$? . -> timer start). The average pitch of the hand (rotation about the x-axis). Again, a sizeable delta indicates the user has begun to perform the requested action. Like with exercises 1 and 3 we again use this sizeable change as an indicator to start the timer (Δ . hand pitch $> n$? -> timer start).

We now move onto the logic behind the rehabilitation exercises the user is required to perform. We will look at the first exercise where the user is required to go from holding their hand at rest, to forming a clenched fist before finally returning their hand to a resting position.

Here we check the current exercise index and ensure that there are still repetitions left for the user to perform. We then present the description/brief for this exercise if we have not already done so. Lastly, we use the first of the two metrics recorded during calibration to check for a sizable delta in the vector stemming from the palm to the tip of the front-most finger, this means the user has begun to move their hand and so we start the timer.

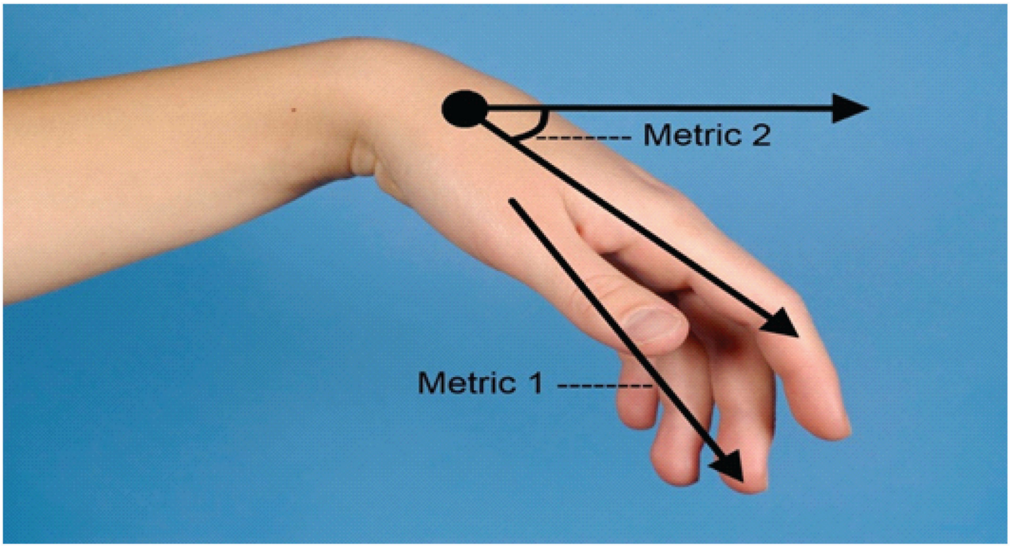
Figure 10. Rehabilitation exercise screen



The system checks for 5 fingers; this indicates a hand at rest. When this condition is met, we psent the time for the current repetition and store the time if it is a new personal best before prompting the user to continue to the next rep by updating the exercise instruction field. The second condition we check for is a finger count of zero (along with the necessary prompt having been shown/not shown), a finger count of zero indicates a clenched fist. At which point we update the exercise instruction field and toggle the prompt displayed Booleans. The second exercise (Wrist Flexion & Extension) uses similacore logic but uses the second of the two metrics recorded during calibration (hand pitch) to help decide when the timer should be started and instructions. The third and final exercise (Three Jaw Chuck Pinch) uses the exact same logic as the first exercise (Fist Clench) and will therefore not be covered. The only notable difference between them is the number of fingers being checked for at each stage of the exercise. Since the third exercise uses the thumb, index finger and middle finger, we check for 3 fingers instead of 5 followed by 1 instead of 0. After the data from the Leap Motion has been collected and used to progress the exercises, the last remaining task for the current loop iteration is to update the 3d hand model. The 3D hand model used in the LMRS is powered by version 3.5 of XNA and uses data from the Leap Motion to animate the bones of the model. Before animating the hand however, we must first calculate two key vectors, the angles between which will then be used to animate the hand model by setting the joints equal to these angles. The first of these two vectors covers the distance between the centre of the palm and the base of the finger in question; the second of the two vectors covers the distance from the base of the finger to the finger tip, these can be seen in figure 12.

However, before we can even calculate these two vectors, we must first calculate the

Figure 11. Metrics used to recognise user initiation of exercises



base of the finger itself as this data is not readily accessible via the Leap Motion SDK, however, the Leap developers do provide a means to calculate this in the SDK documentation (Leap Motion, 2013). These three vectors (finger base, palm to base and base to tip) along with the resulting angle data e calculated twice. Once for the thumb (using the left-most finger member provided by the Leap Motion SDK) and once for the four remaining fingers (all of which mimic the front-most finger member again provided by the Leap Motion SDK). Due to the Leap Motions lack of skeletal tracking however, it is currently near impossible to reliably identify individual fingers; left-most, right-most and front-most are the only ones reliably accessible through the SDK at present and even then are ambiguous (the left-most finger is the little finger of your left hand and is, at the same time, the thumb of your right hand for example).

Once these vectors have been calculated, they are then used to calculate the angles to which the joints in the 3d hand model will be set. For this, we borrow the following quadratic equation from (Hillerbrand, et al., 2005): $q_{\alpha,\beta} = 0.23 + 1.73d + 1.5d^2$.. Originally, this equation was used to define the relationship between the bending angle of the outer-most and middle phalanx (α) and that of the middle and inner phalanx (β), with d denoting the distance between the base joint and fingertip relative to the finger length. For the LMRS, we use this quadratic for the 3d hand model; substituting the values 0.66 and 0.33 for α and β respectively for the index, middle, ring and little finger, for the thumb, we only use the 0.33 value. In addition to this, we multiply by the angle between the finger-base and the palm. This helps the finger bend in a realistic fashion despite only having the angle between the palm and finger base as our only accessible/calculable value. We next calculate a pitch and yaw for the hand model (with pitch describing rotation about the x-axis and yaw describing rotation about the y-axis). To do this we can simply use the normalised direction property of the hand object in the Leap SDK, the only modifications we make are to tone down the yaw as leaving this value unaltered or too high was found to cause difficulties. The final result is shown in figure 13.

We move now to the final part of the system with which a typical patient user may interact, this being the viewing and graphing of results

Figure 12. Vectors used for angle calculation

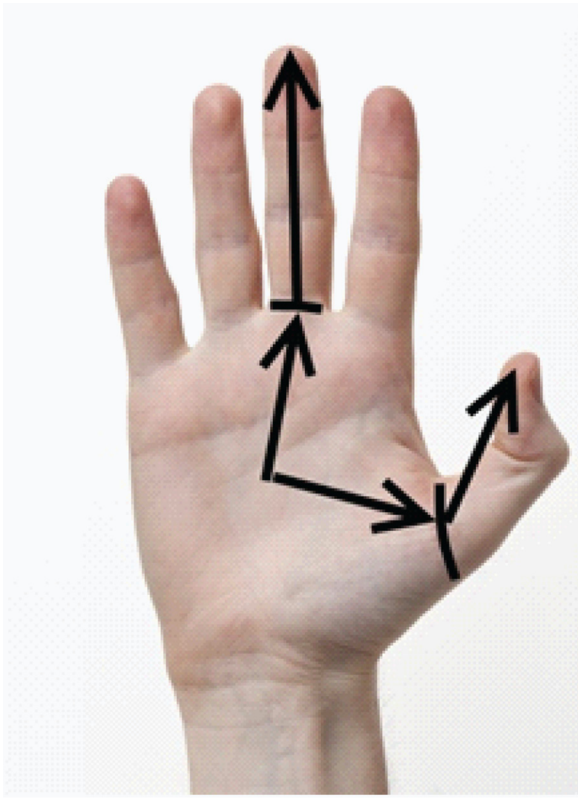


Figure 13. Demonstration of XNA-powered 3d hand model

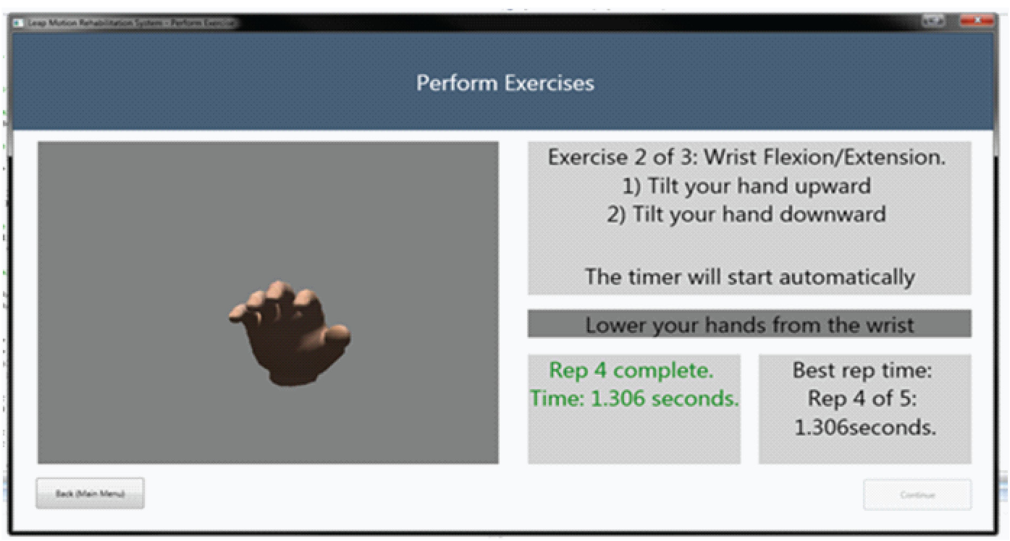
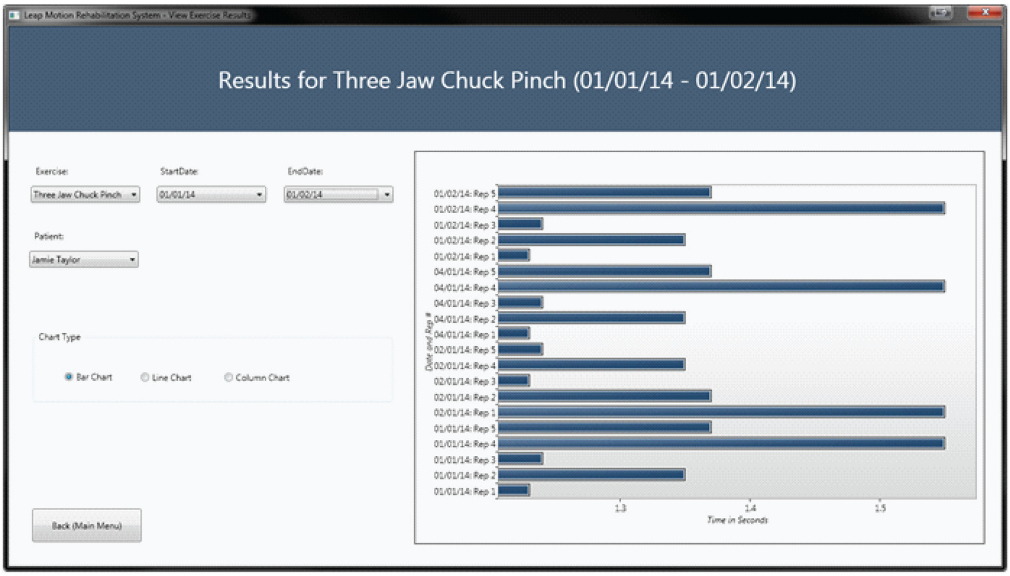


Figure 14. LMRS exercise results screen



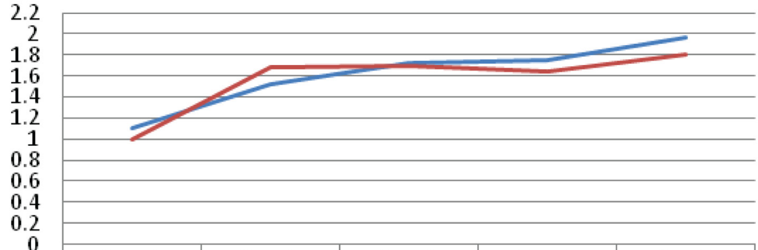
for that user, this functionality can be seen in Figure 14. This is the clinician variation of the form being shown, however the main difference between this and the patient variation is the patient combo-box which is not visible for a patient user. We show the fully-featured clinician version to avoid needless repetition. This mention of form variation depending on user type would make the load and unload code a logical place to start. Note that we are using a custom constructor and decide whether or not to make the patient selection functionality available depending on the user-type argument passed to us.

4. EVALUATION

Throughout initial development, the most commonly used testing methods were those of unit and regression testing. With unit testing used to test individual functionalities and units of code. Unit testing for the LMRS took the form of compiling and running the system to check that it is first: stable and secondly: that it functions as expected/designed. Regression testing was used in addition to unit testing to confirm correct and expected behaviour after notable changes/refactoring. Regression testing for the LMRS took the form of compiling and re-running the system, with the aim of testing certain functionalities which had seen significant re-working, commonly as a result of the prior mentioned unit testing. This was done before testing the system against more formal, drafted test cases.

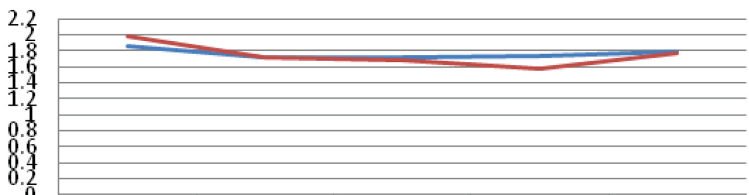
The first formal means of testing the LMRS was through the use of conventional test-cases. These test cases describe the typical usage patterns of both a clinician and patient user. The tests include basic sanity testing (the ability to detect and reject false credentials and other 'junk data') in addition to testing the various components of the system (can exercises be performed without issue, does the results graph show correctly etc…).The issues uncovered by these test cases were largely XML related. For example, both crashes on the results screen (for either patient or clinician) were the result of empty XML elements. One due to potentially missing session elements (if a user quits before completing an exercise for example) and the other due to an error in the original remove

Graph 1. Exercise 1: Fist clench



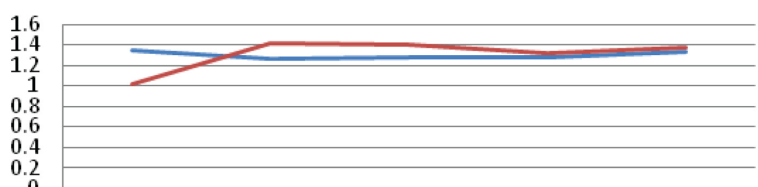
	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5
Video Reference	1.1	1.516	1.726	1.753	1.96
LMRS	0.99	1.679	1.695	1.646	1.807

Graph 2. Exercise 2: Wrist flexion and extension



	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5
Video Reference	1.85	1.711	1.721	1.732	1.782
LMRS	1.976	1.713	1.686	1.583	1.766

Graph 3. Exercise 3: Three jaw chuck pinch



	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5
Video Reference	1.34	1.26	1.27	1.273	1.33
LMRS	1.008	1.409	1.394	1.322	1.368

Table 2. Exercise repetition time variations

Repetition #	Exercise 1 – Fist Clench	Exercise 2 – Wrist Flexion and Extension	Exercise 3 – Three Jaw Chuck Pinch
1	-0.109	-0.116	-0.322
2	0.107	-0.003	0.149
3	-0.031	0.035	0.124
4	-0.106	0.149	0.267
5	-0.153	0.153	0.076
Average	**-0.0584**	**0.0436**	**0.0588**

patient code which would remove all child elements of the patient but not the patient element itself. In addition to this, testing revealed a lack of any suitable prompt for exiting while an exercise session was in progress. A prompt was added in response to this to keep the system in-line with its initial requirements, in this case, the requirement of keeping the user informed at all times.

One of the important aspect of the LMRS is that it provides highly accurate timings of exercise repetitions; if the LMRS cannot provide accurate exercise repetition timings then any medical relevance/usefulness of the timings and that of any other LMRS-generated data is dramatically reduced. To measure the accuracy of the LMRS in this respect, the system has been compared against video references; actual video recording of the exercises being performed. The timings recorded by the LMRS are then compared against the timings taken from the video reference (acquired by measuring the time taken in video for a repetition to be performed). Graphs 1, 2 and 3 show the accuracy of the LRMS relative to the video reference for each of the three exercises (Fist Clench, Wrist Flexion & Extension and Three Jaw Chuck Pinch). This data has been collected by performing each exercise three times (three LMRS sessions and three reference videos) and taking the average time for each rep (1, 2, 3 etc…).

As we can see in graph 1, deviations in the times recorded by the LMRS compared to those in the reference video are minimal (often around 100 milliseconds). This trend is maintained in exercises 2 and 3, as seen in graph 2 and 3.

It is worth noting however that the one consistent area of variation between the LMRS and the reference video is the first repetition of each exercise, this would suggest that adjustments and/or refinements to the values used in the timer related conditions (when to start/restart) may be in order for future iterations.

In addition to the repetition timings, the deviation observed for each exercise has also been calculated and are presented in table 2. This is an important – if not critical – metric for the LMRS and any rehabilitation system of this nature and will be a key metric used to judge any future changes or additions made to the LMRS (a more accurate version of the hand model cannot come at the cost of a loss in repetition timing accuracy for example). As with the repetition time data discussed above, this deviation data has been calculated by taking the average deviation for each repetition across the three sessions and then taking the average (the deviation value for rep 1 in exercise 1 for example is the average rep 1 deviation observed for that exercise across the three sessions).

The results are encouraging. Despite the Leap Motion being an as yet new and untested device, we see that the average inaccuracy (deviation) in the timings measured by the LMRS is less than 100 milliseconds and rarely is the 100 millisecond barrier broken for any individual repetition.

5. CONCLUSION

This research saw us set out with the aim of researching and subsequently developing a rehabilitation system for those with hand injuries and to do so using the Leap Motion as our medium, rather than more traditional technologies like data-gloves. The system was to allow a user to perform rehabilitative exercises while receiving stimulating feedback via a real-time animated model. The system was then required to store this data for later viewing by either the patient or a clinician. Tess took the form of comparing the exercise repetition timings as recorded by the system to those observed from a video recording of the same exercise. These tests have proven that any differences between repetition timings as recorded by the system are minimal (rarely above 100 milliseconds and below 100 milliseconds on average) when compared to those observed from a video recording, suggesting the system holds much promise. Ultimately, we were able to craft a functional rehabilitation system using an entirely new medium – the Leap Motion. The price and relative accuracy of this device in addition to its other unique qualities mean the LMRS potentially represents the beginning of a promising new avenue with regards to use of technology in rehabilitation.

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Jamie Taylor (BSC) is a graduate in Computer Science of the University of Ulster. He is currently studying for an MSc. His research interests include programming languages and game engines.

Kevin Curran BSc (Hons), PhD, SMIEEE is a Reader in Computer Science and group leader for the Ambient Intelligence Research Group at the University of Ulster. Dr Curran has made significant contributions to advancing the knowledge of computing evidenced by over 800 publications. He is a regular contributor to BBC radio & TV news in the UK and quoted in trade and consumer IT magazines on a regular basis.