Automated Variable Resistance System for Upper Limb Rehabilitation

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Abstract

After neurological injury such as stroke, upper limb paresis and loss of hand function leads to lower activity of the paretic limb and loss of independence. The strength of the paretic upper limb is strongly related to measures of activity. Robot-assisted therapy, along with augmented reality leads to increased motivation to perform exercises and improvements in motor function, but costs are high so clinical uptake is rare. A device was developed to allow a computer to control the exercise effort for a table-top, augmented reality therapy based on a computerised arm-rehabilitation skate. Various methods of applying and controlling the therapeutic exercise effort have been evaluated in designing the device, which should be portable and suitable for home based use. A vision based motion tracking system captures the movement of the device, so a computer can be used to monitor and control the exercise effort. The novel design of the rehabilitation system allows computer controlled resistance to movement, as well as integration with exercise stimulating games and windows-based tasks. This provides the patient with a home-based exercise platform which provides stimulating experience in his/her physiotherapy.

1 Introduction

Strokes are the greatest cause of serious long term disability in the United States. Every year about 795,000 Americans suffer from a new or recurrent stoke [2009a]. Loss of hand function as a result of upper limb paresis after a stroke greatly reduces the probability that an individual can return home and to premorbid activities [Nakayama *et al.,* 1994; Hunter *et al*., 2002].

Unfortunately, the outcome of rehabilitation for an impaired upper limb is generally poor. For example, fifty percent of stroke survivors have impairment of upper limb function and of these, only 15% can expect to regain function from a "traditional" physiotherapy program [Harris and Eng, 2007]

There is increasing interest in using robotic devices to aid rehabilitation therapy following neurologic injuries such as stroke and spinal cord injury [Reinkensmeyer *et al*., 2004; Riener *et al*., 2005]

Rehabilitation devices for upper limbs can be classified into two broad categories based on the interaction of the patient with the device, end-effector and exoskeleton. End-effector based devices may be simpler to adjust to accommodate different patients, but arm posture is not fully determined and there is a risk of joint injury to the patient. Exoskeleton devices are able to determine the position of each joint but must be set up so anatomical axes align with robot axes and may lack the full range of motion for each joint.

End-effector devices may be either bilateral or unilateral. The Reha-Slide, which is shown in Figure 1, is a bilateral, end-effector tabletop device for the upper limb rehabilitation of stroke patients [Hesse *et al*., 2007]. The bilateral exercise trains the shoulder, elbow and wrist joints, using the unaffected arm to assist movement of the paretic arm. An interface with a computer is achieved by using a laser mouse, enabling the user to play computer games and providing motivation to perform more exercises. One issue with bilateral devices is that they are only suitable for the rehabilitation of unilateral injuries and would be of little benefit to a spinal cord injury patient with paralysis of both arms. Robotic, unilateral end-effectors devices such as the MIT Manus [Volpe *et al*., 2000] and GENTLE/s [Coote *et al*., 2003] show that robot-mediated therapy does improve the recovery of motor skills.

Figure 1. The Reha-Slide a bilateral, end-effector based device

Passive exoskeleton devices such as the T-WREX and ARMEO (Figure 2) support the limb against gravity, while active exoskeleton devices such as the ARMin are capable of moving the limb in the desired motion. Studies showed that the ARMin was capable of improving the motor performance of patients [Reiner, 2008].These devices allow more success in completing movements and increase motivation and activity through the use of virtual reality tasks or games [Reinkensmeyer and Housman, 2007].

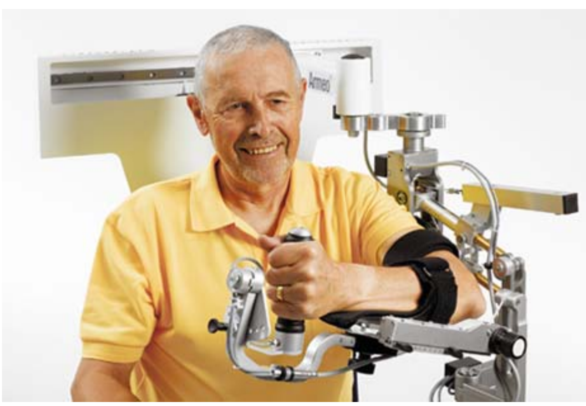

Figure 2. ARMEO – a passive exoskeleton device

Combining robotic therapy and virtual reality leads to improved motor skills and function, but the cost is relatively high [King *et al*., 2009]. Advantages of using robotic devices in rehabilitation therapy include quantitative measurements, the ability to record data and a reduction in the amount of therapist time required. Disadvantages with these devices are that they are expensive and difficult to set up, even within a rehabilitation hospital, so they are not viable for home based use. Home-based therapy has been shown to be considerably less expensive than institutional rehabilitation [Coast et al., 1998; Leff et al., 2005] so there is a need for cost-effective rehabilitation technology.

The arm skate concept described was shown to be a useful device for stroke rehabilitation therapy [King *et al*., 2009] and could potentially be simple for therapists to set up and affordable for home based rehabilitation. The arm skate is an affordable table top device which can assist patient rehabilitation in their own home. A castor wheel is in contact with the table and a mechanically adjustable brake is used to provide varying levels of resistive force [De Ruiter *et al*., 2008]. Although the device provided resistance to the patient's arm movements, it was cumbersome and required manual adjustment by a clinician.

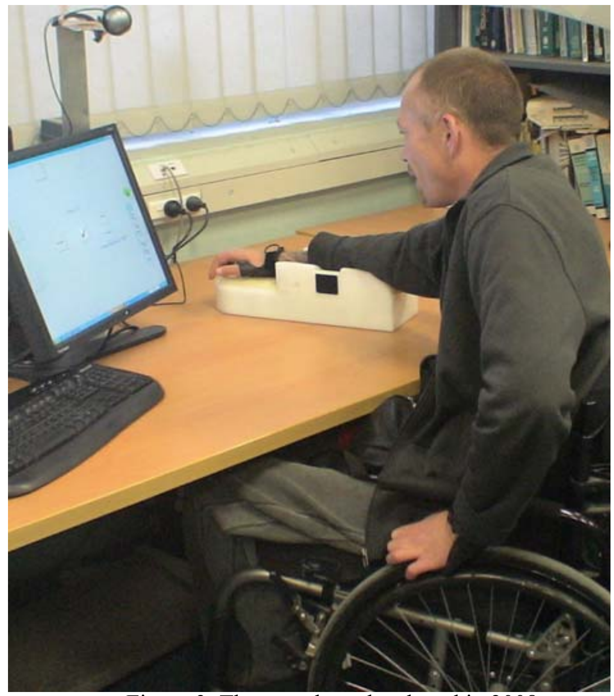

Figure 3. The arm skate developed in 2008

The goal for the research described here is to implement computer controlled adaptive resistance which will allow the device to automatically change the resistance level according to the patient's ability. As the patient's movement and strength improves, the controller will detect this and increase the difficulty of the exercise by increasing the resistance level. By implementing computer controlled resistance in the device, the arm skate will be more practical for long-term rehabilitation of a user in an unsupervised environment such as at home.

The outcome for the project is to have a device that is user friendly and suitable for home use. The device will be interfaced to the computer so the user can play an interactive game which will motivate the user to exercise for longer periods.

This paper firstly presents the system conceptualisation, secondly the electromechanical design followed by test results of the variable resistance exercise system and finally a discussion about the functionally of the arm skate.

2 System Conceptualisation

2.1 Device Specifications

Through discussion held with physiotherapists from Burwood Academy of Independent Living, Christchurch New Zealand and the team's past experience with people using gravity supported exercise systems [[King *et al*., 2009 ; De Ruiter *et al*., 2008].] a list of specifications for the arm rehabilitation device was identified – the automated variable resistance arm skate. The specifications include:

1. Functionality
   - Variable resistance up to 20N of force in two dimensions
   - Smooth travel through the full range of motion
   - Resistance controlled through a standard computer
   - Universally compatible on recent Windows operating systems
   - Straightforward operation to inexperienced users
   - Exercises may be carried out on a home table top
2. Safety
   - Ensure no rubbing of arm
   - Ensure no arm slide
   - Ensure heat dissipation from resistance system is sufficient to eliminate risk of burns
3. Ergonomics
   - Can be used for either arm
   - Supports patients with spasticity
4. Cost
   - Low cost device which could be made readily available to patients and hospitals
   - Uses standard commercially available PC hardware

2.2 Concepts for Rehabilitation Device

From the specifications and concept-generation exercises, several concepts were derived for the wheel system and the resistance system. The feasibility of each concept was checked before choosing a set of possible solutions.

For the wheel system the following concepts were considered:

- Castor wheel
- Ball wheel
- Omni-wheel.

For the resistance system the following concepts were considered:

- Electromagnetic brake
- Electromotive brake
- Table contact pad
- Belt friction
- Brake pad in contact with wheel

2.3 Selection Process

A weighted selection process was used to select the final concepts for the wheel system based on key criteria of:

- Ability to provide assistance (or be modified to do so)
- Compactness
- Weight
- Turning arc
- Travel smoothness
- Reliability
- Simplicity
- Cost

For the resistance system, the key selection criteria were:

- Ability to provide assistance (or be modified to do so)
- Compactness
- Accuracy of resistance control
- Power requirements
- Availability of parts
- Reliability
- Simplicity of control
- Cost

Each criterion was assigned a weighting from 1 to 5, which was multiplied by the 1 to 5 score of the concept. The results of the evaluation are tabulated in the decision matrices below, Table 1 shows the wheel evaluation and Table 2 evaluates the resistance system.

Table 1. Evaluation matrix for 'wheel' selection

Criteria	Weighting	Caster Wheel	Ball Wheel	Omni Wheel
Assistance	4	3	5	5
Compactness	2	3	1	2
Weight	3	3	2	3
Turning Arc	1	3	5	4
Travel Smoothness	4	3	4	4
Reliability	3	3	1	3
Simplicity	3	3	1	3
Cost	3	3	1	2
Total		69	58	77

Table 2. Evaluation matrix for resistance selection

Criteria	Weighting	Electric Brake	Electro-motive	Table Contact Pad	Belt friction	Wheel Brake Pad
Assistance	4	3	5	1	2	2
Compactness	2	3	2	4	2	4
Weight	3	3	3	3	3	4
Accuracy of resistance control	3	5	4	2	3	2
Power Requirements	2	2	3	3	3	3
Availability of Parts	3	4	5	3	3	3
Reliability	3	5	4	3	4	3
Simplicity of control	3	4	1	3	3	3
Cost	3	4	2	4	3	4
Total		97	87	72	75	79

A system which uses omni-wheels and an electromagnetic brake emerged as the preferred choice. This system will be simple to implement and control while providing smooth omni-directional travel and an accurately controlled resistance level.

2.4 System Functionality

The automated variable resistance arm skate is a table based augmented reality exercise platform. It is portable, compact and easy to set up. The mouse-like device provides the full range of motion required and can be used by patients without assistance.

Figure 4 shows a high level functional diagram of how the system delivers the desired resistance level. The device has both manual and automatic resistance adjustment, which can be chosen by the user. In the manual adjustment mode, the new resistance level is sent directly to the device via a wireless Bluetooth connection. The automatic adjustment uses position and velocity data captured by the webcam to calculate a resistance level. The Bluetooth signal is received by a Bluetooth module on the device which sends the data to a microprocessor. The microprocessor controls the brake circuit, varying current to deliver the required resistance level.

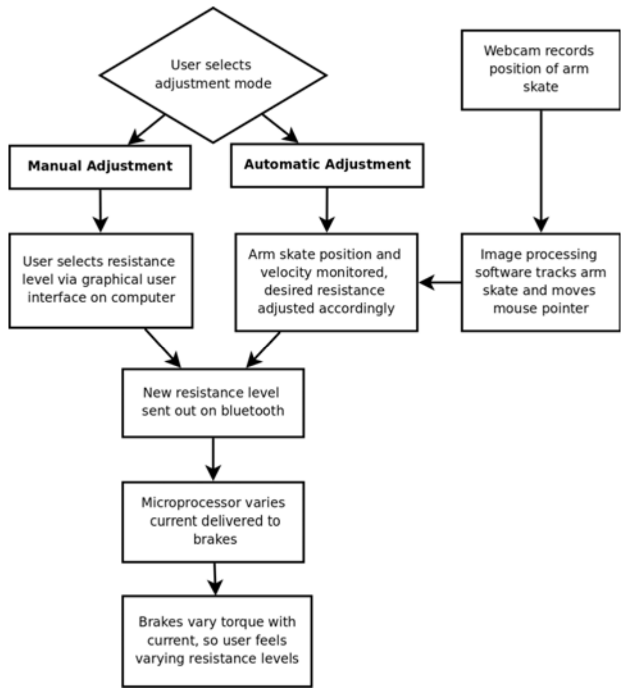

Figure 4. System resistance control flow diagram

The webcam, which monitors the arm skate, and image processing software allow the arm skate to be used as a computer mouse. The mouse driver interface means that the arm skate can be used for specialised exercise games or general software applications. Positional data for the arm skate is directly available and the velocity data can be calculated by differentiation.

3 Electromechanical Design

3.1 Variable Resistance

The most important feature developed during this project is the addition of computer controlled variable resistance to the arm skate. This can be programmed to replicate a viscous damper or use zone based resistance. In a viscous damper, the resistance level is proportional to the velocity of the arm skate. In a zone based resistance scheme, the patient's range of motion is divided into zones and differing resistance levels are applied in each zone.

The skate travels on two omni-wheels (Kornylak Corporation product code FXA310), shown in Figure 5. These consist of a wheel with several smaller rollers around the circumference allowing unrestricted motion perpendicular to the wheel's direction of rolling. Torque can be applied only in the direction of rotation of the wheel. The omni-wheels are mounted perpendicular to one another allowing resistance to be applied equally in any direction when torque is applied by the electromagnetic particle brakes.

Electromagnetic particle brakes were chosen for their ease of control. The selected model (Placid Industries product code B2-6-1M) is current controlled, with the braking torque directly proportional to the brake current, which allows for accurate and automated control of the resistance level.

Figure 5 shows a photograph of the major components of the arm skate. The omni-wheels and electromagnetic particle brakes are secured in an aluminium housing. In the final design all the components will be mounted in an outer shell.

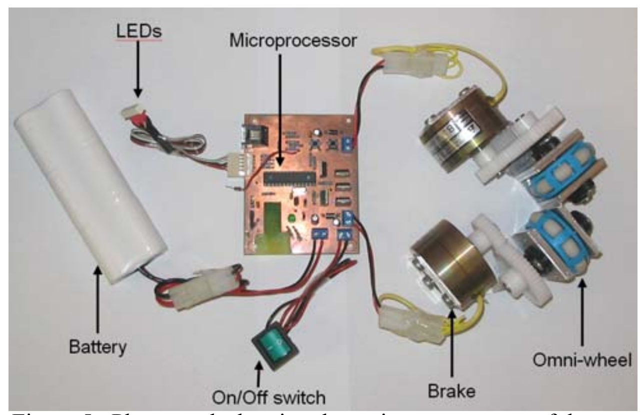

Figure 5: Photograph showing the major components of the arm skate

3.2 System Mechanical design

The outer shell of the arm skate is moulded from 3mm PVC. This provides the required rigidity and has the advantage of being lightweight and easy to manufacture. The PVC has a smooth surface which is hygienic, easy to clean and corrosion resistant.

Attached to the underside of the shell at the front of the skate is the housing containing the wheels and brakes. The housing is made from aluminium box section with the different sections bolted together along with the flange mounted bearings. The housing is bolted to the outer shell of the arm skate, providing good stability. Due to sizing and torque requirements the wheels must be coupled to the brakes with a gear ratio of 2:1 which is achieved using spur gears on parallel shafts.

The omni-wheels are mounted directly below the base of the user's hand support in order to maximise the weight on the wheels and therefore the maximum possible resistance encountered by the user. The replacement of the conventional castor wheel with the pair of omni-wheels has the advantage of reducing the backlash caused by the castor arc in the previous design [De Ruiter *et al*., 2008].

The rear of the device is supported by two ball castors mounted on the underside of the shell. It is important that both omni-wheels remain in contact with the table top surface during operation so that friction grip is not lost. The small amount of flexibility in the outer shell will ensure this is the case.

The user's forearm is supported by the shape of the outer shell of the skate. The hand piece is interchangeable to allow the skate to cater to a broad range of user needs, particularly if the skate is used in a clinic treating many patients.

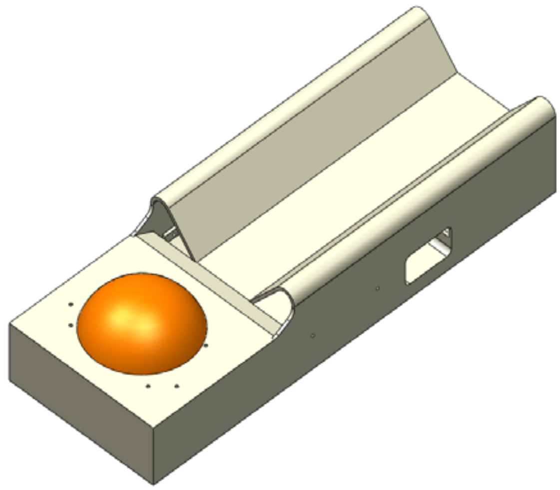

Figure 6a: Isometric view from the top of the arm skate

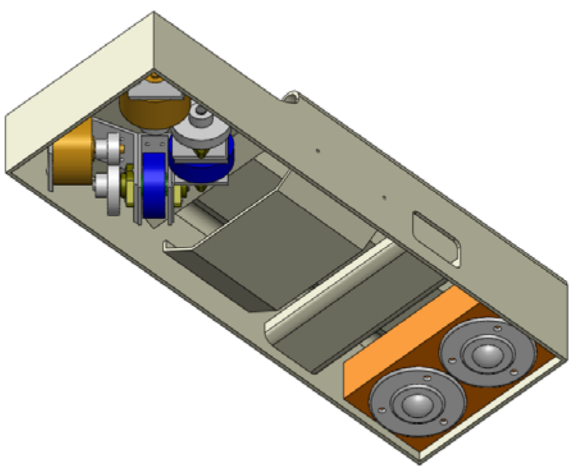

Figure 6b: Isometric view from the bottom of the arm skate

Isometric views of the arm skate are illustrated in Figures 6a and b. Figure 6a shows the outer shell and the hand piece. Figure 6b illustrates how the housing and ball casters are positioned at the ends of the arm skate, with provision for housing the battery and circuit board in the middle.

3.3 System Electronic design

The hardware on the arm skate has three main features: a Bluetooth module to allow wireless control from the PC, a microcontroller and a brake control circuit. These components are powered by a rechargeable battery.

The host computer sends the desired resistance level to the Bluetooth module on the arm skate. The microcontroller receives resistance level data from the Bluetooth module and updates the desired resistance level accordingly. A pulse width modulation (PWM) port is used to control the brake circuit shown in Figure 7, with the duty cycle being adjusted to vary the resistance level. The microcontroller also controls LEDs to alert the user to faults, if necessary, or indicate the resistance level.

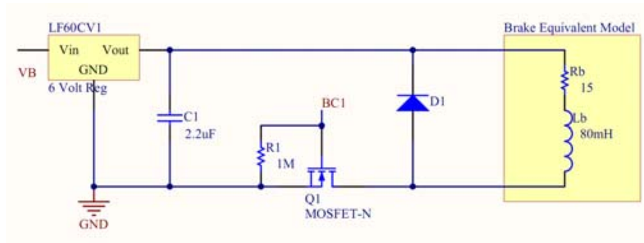

Figure 7. Brake control circuit with model of brake

The electromagnetic particle brakes are controlled by individual MOSFET based switching circuits such as that shown in Figure 7. The PWM input (BC1) controls the average current delivered to the brake by rapidly switching on and off the MOSFET. The diode maintains current flow when the MOSFET is switched off. The brakes deliver a braking torque which is directly proportional to the current. Figure 7 shows an equivalent series inductor resistor circuit which models the behaviour of the brake. Switching is carried out at speeds in the order of 1 kHz to ensure continuous current can be maintained so the braking torque is applied smoothly.

3.4 Host Computer Software

The arm skate uses mouse tracking software and resistance adjustment software to allow the user to perform rehabilitation exercises while interacting with a computer.

The mouse tracking software developed by HIT Lab, University of Canterbury, New Zealand, is a machine vision program that runs in the background. This software uses a webcam mounted overhead to view the arm skate moving across the table top. It tracks the movement of a particular colour patch which is attached to the arm skate and preselected in the software. The position of the colour patch in the image is then translated into a position on the screen, effectively behaving as a normal PC mouse cursor but without position drift.

The resistance adjustment software is a user controlled application that communicates via Bluetooth with the arm skate. The user has the option of two modes of operation, manual or automatic resistance adjustment. With manual adjustment the user can set the level of resistance they feel comfortable with through a slider bar. When the device is in automatic mode it can either adjust the resistance according to how fast the mouse is moving (viscous damping) or by setting regions where extra resistance may be recommended by the clinician requirements during rehabilitation. For example, regions further away from the user may have the resistance set low as they may be difficult for the user to reach. A more detailed view of the automatic adjustment procedure can be seen in Figure 8.

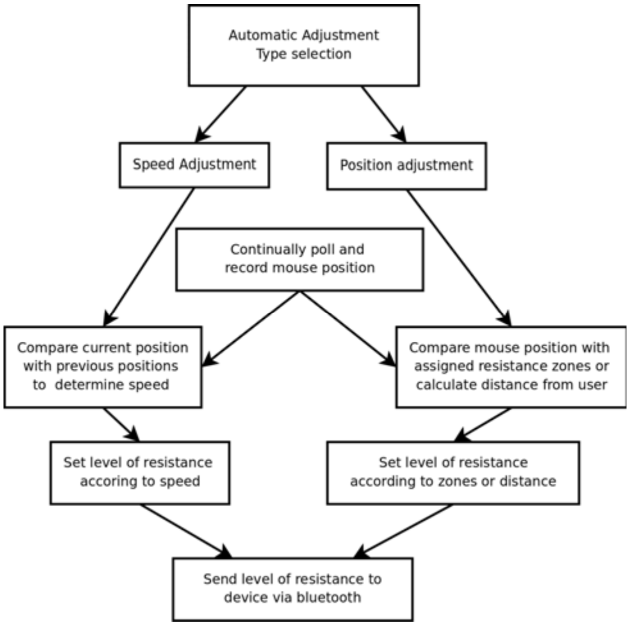

Figure 8. Flow diagram outlining the process for automatic adjustment of resistance

Figure 8 shows the flow of the automatic adjustment procedures. The first is a user selection, where the user chooses if the resistance should be adjusted according to the motion of the mouse or its position on the screen. The next step is that the position of the mouse is logged and calculations are made to determine the speed, position or distance. The calculated figures are processed into a resistance output that is sent to the device and the process repeats.

4 Results

In order to design the arm skate, the electrical and physical characteristics of key components such as the electromagnetic particle brakes were determined. The completed arm skate was also tested to quantify the resistance delivered and evaluate the accuracy of the control.

Initial testing on the electromagnetic particle brakes showed that their circuit behaviour can be modelled as a series inductor resistor circuit, with the braking torque proportional to the brake current. The resistance of the brakes is 15Ω. After determining the time constant of the brakes, an inductance of 80mH was calculated for the model.

Testing was done on the brake control circuit to ensure that a suitable current can be delivered to the brake. The microcontroller was setup to generate a 3.8 kHz PWM signal with a 50% duty cycle. At 50%, the largest amount of current ripple occurs. A 1Ω resistor was wired in series with the brake to allow the current to be measured. Figure 9 shows that the ripple current is small, equivalent to 20mA with a mean current of 140mA. Note that 0V is in the centre of the screen in Figure 9. This was found to be satisfactory as continuous current is maintained and the frequency is too high to be felt by the user.

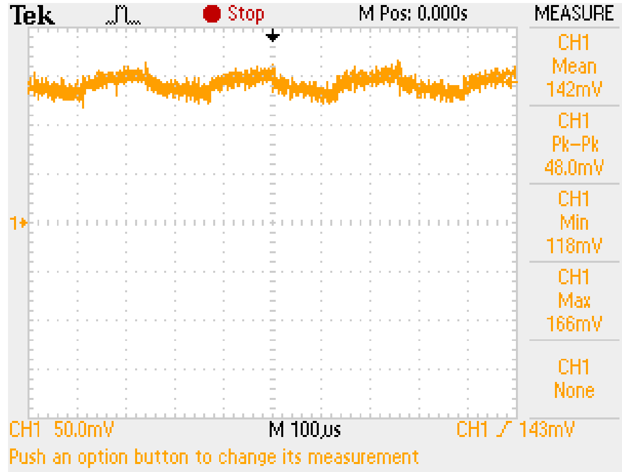

Figure 9. Oscilloscope snapshot showing the ripple current in the electromagnetic particle brake

The battery life of the device will need to be long enough for the duration of an exercise session. The battery has a capacity of 2A hours. The electromagnetic particle brakes draw up to 400mA each at 6V. The microprocessor will use less than 50mA while the Bluetooth will use 30mA under normal operation (these both run at 3.3V). This gives an expected battery life of at least 2 hours.

Initial testing of the housing showed that the use of omni-wheels allow controlled movement in any direction. When used on a rubber surface, the omni-wheels have a coefficient of static friction of $\mu_s = 0.6$. The arm skate weighed 3kg, so approximately 20N of resistive force may be applied by the device before the omni-wheels begin to slip.

Once the arm skate construction was completed, tests were performed to quantify the resistance delivered. A high density EVA mat was used to enhance travel smoothness and resistance range. With a 0.5kg weight resting on the arm skate, to simulate the weight of a hand, the resistance level varied almost linearly between 7 and 22.5 N. The resistive force increased linearly until the omni-wheels began to slip, as shown in Figure 10, proving that the resistance control worked well. On a wooden table surface the maximum resistance was much smaller, as the omni-wheels had a lower coefficient of friction on the smooth surface and they began to slip earlier. Future testing of the device with clinicians will establish which resistance range is most beneficial for rehabilitation.

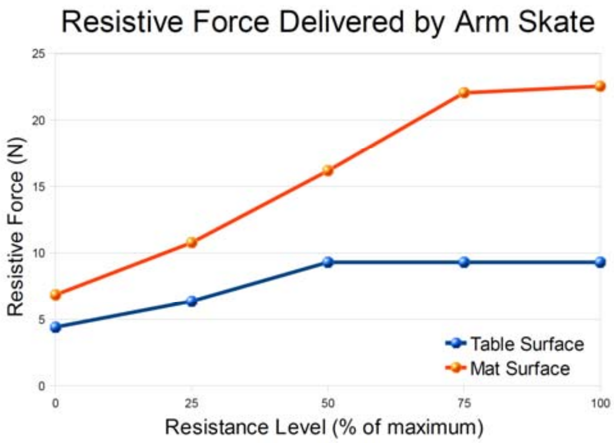

Figure 10. Test results from the completed arm skate

A major advantage that the arm skate has over currently available systems is that it is affordable and suitable for home based use. The device can easily interface with a computer and be used by the patient on a desktop. The arm skate also has the added advantage of being wireless, requires no external power supply and no manual adjustment by the user.

5 Discussion

The objective of the Computer Controlled Variable Resistance Exercise System for Upper Limb Rehabilitation project was to further develop the arm skate and implement computer controlled adaptive resistance. With the unique combination of omni-wheels mounted at 90 degrees to each other and electromagnetic particle brakes, movement and resistance can be applied in any direction on a two dimensional table top surface. The use of electromagnetic particle brakes and an onboard microprocessor allows for varying levels of resistance to be applied by using PWM control to vary the brake current. The resistance level can be altered between 7 and 22N through a computer program which allows manual or automatic adjustment. In the automatic adjustment mode the resistance applied is based on data obtained from the machine vision is used to apply resistance either as a viscous damper or zone based system.

In the system design many factors were taken into account these included but were not limited to: health and safety, aesthetics, portability, usability, cost. The prototype was sized based on the information collected from last year. To ensure patient hygiene and safety when using the device all surfaces have a smooth finish.

From testing, the battery life was found to be at least 2 hours, this will allow multiple exercise sessions to be carried out on a single charge of the battery. The arm skate can deliver a resistance force that can between 4 and 22N, depending on the surface used. The computer software developed allows accurate control of the resistance level and allows the implementation of automatic resistance adjustment algorithms. Further testing during clinical trials will determine the range of resistive force which is most beneficial for rehabilitation.

The system is modular and allows the battery, circuitry or wheels to be changed or modified in future development. This system allows a clinician to control a rehabilitation programme that will update automatically as progress occurs. Achievement milestones of resistance levels that a patient can overcome and speed of movement can be set whereupon certain rehabilitation procedures may be altered. The device can be programmed to increase the intensity of the desired exercise in a similar manner to video games which become harder as levels of achievement are attained. The arm skate also has the potential to provide different types of resistance. For example, viscous damping is a resistance type that is considered more sophisticated than simple resistance for rehabilitation [Marchal-Crespo and Reinkensmeyer, 2009].

One disadvantage of this device compared with current available is that it does not provide a larger range of resistances. The maximum resistance is limited by the friction force between the omni-wheels and the table surface. The arm skate does have benefits that are not incorporated in other rehabilitation devices such as portability, ease of use by patient and no need for clinicians to supervise the exercise. The arm skate offers an affordable and practical solution to home based upper limb rehabilitation.

Programming enhancements may be added to provide an adaptive system that can determine areas of reach that a patient has particular difficulty with. Once these are defined then the resistance can be adjusted to provide a more enjoyable rehabilitation experience for people with severe disabilities.

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