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# Occupational and physical therapy Using a hand exoskeleton based exerciser


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*Abstract*—**Hand therapy is a major sector of physiotherapy and one of great importance. The impairment of the hand and generally of the upper limbs can be the cause of social and financial hardship and a serious cause of physical and emotional deterioration. Major efforts are directed into developing therapy methods and procedures in order to standardise and therefore successfully apply treatment regimes in a wide scale. Although, the lack of scientific measurements of statistical value that the current methods suffer due to the mostly empirical nature of examination, assessment and treatment does not assist this endeavour. This paper presents an exoskeleton based system for the physical and occupational therapy of the hand in an interactive VR environment. This system enhances the existing therapy methods with the introduction of accurate and repeatable finger motion and force measurement, interactivity, potential for great exercise assortment and statistical registration and evaluation.**


## I. INTRODUCTION

The importance of having a normally functioning hand for an independent and active life needs no emphasis. The hand is an organ of grasp as well as sensation, fine discrimination and exquisite dexterity. Unfortunately, the incidence of injuries directly affecting the hand has risen dramatically in the recent years [1]. These injuries include traumatic injuries, congenital deformities, neurological and arthritic conditions, and regional pain syndrome of the hands.

At the rehabilitation phase, hand therapist employs two groups of exercises: physiotherapy exercises and occupational therapy exercises. Physical therapy exercises focus on basic gross mobility skills such as moving specific joints and strengthening specific muscles. Occupational therapy generally concentrates on activities of daily living. Both groups of exercises aim to reduce pain, restore function and promote as much independence as possible [2].

Other treatment techniques include passive joint mobilisation and soft tissue work such as deep friction massage. Specific exercise programs are prescribed to mobilise, strengthen, and desensitise. Return to optimal activity levels is enhanced with the provision of aids and appliances [2,3,4,5].

However conventional hand therapy has a number of disadvantages, which are listed below:

i) Regaining motor skills needs intensive and repetitive training.

Repetition though, is a major disadvantage of the conventional therapy, because it relies on the patient's motivation to do the exercises prescribed [6].

ii) Subjective and irreproducible measurement.

Initially the patient is examined for the presence of pain and any loss of strength, sensation, range of motion, and structure. The results are utilised to produce a numerical assessment of impairment used to evaluate the patient's progress over time. Functional evaluation is currently accomplished by subjective observation of patient performance on standardised tests for motor skills. Examinations and calculations though can be time-consuming, expensive, and subject to observer error. In addition, reproducibility of measurements becomes an issue whenever different examiners evaluate the same patient, which makes it difficult to evaluate a patient's progress over time [7].

iii) In many cases simple mechanical devices are used.

Rehabilitation devices are mainly mechanical. Very few of them are sensorised but even those that have sensors are not networked. There is no online measurement of movements. Therefore, therapist cannot monitor the progress.

iv) No remote monitoring or re-evaluation of progress for a patient practising at home.

For the portion of therapy that the patient is doing at home, there currently is no monitoring. This results in varying degrees of compliance with the prescribed exercise regimen, which has negative effects on the treatment outcome.

v) Patients who live in rural areas are forced to travel to urban areas for therapy. This results in additional expenses and disruption in family life.

In addition to the above disadvantages, the numbers of rehabilitative centres that can give such services are limited and their geographical distribution over the most countries is uneven. That means the current system fails to offer many patients the intensive training that is needed for neural reorganisation and functional changes [6].

The adverse financial, social and psychological benefits of the current hand rehabilitation system on the patient, his family and the community as a whole, has motivated the research efforts into innovative hand therapy methods and systems.

In the area of hand disability diagnosis, sensing gloves and hand exoskeletons seem to be very effective, because they provide excellent measurement of hand parameters. DataGlove and CyberGlove, developed by Greenleaf Medical Systems and Virtec have been used as a hand motion analysis and disability diagnosis tools [8,9,10,].

A prototype exoskeleton has been used by [12] as a prosthetic device by patients who have lost muscular control of their hand. A unified system that uses a hand exoskeleton system for both diagnostic and rehabilitation of the hand has been proposed by [13]. Regarding now the hand therapy regimes, one innovative method that has been given attention in recent years is the use of Virtual Environments, which have attributes that make them potential candidates in a new approach to therapy. This is, due to the inherent ability of VEs to simulate real life tasks. Examples of such systems are found in [14,15,16,17].

In this paper a new hand exoskeleton exerciser is presented. The system enables the execution of finger therapy regimes and can also be used as a motion analysis and lost finger mobility diagnosis tool. The first section of this paper focuses on the description of the hand exerciser system. In particular, the mechanical design of the sensory and actuation system of the device are discussed. The next section presents the finger feedback force analysis that relates the forces exerted at the patient's finger segments with the force signals generated by the actuation system. The third section introduces the hand physiotherapy VR system, where a patient performs physical and occupational therapy by interacting with a number of virtually simulated exercises that were designed in a game-like fashion. The last section presents preliminary results to demonstrate the potential of the system as a therapeutic aid for the hand.

## II. HAND EXERCISER EXOSKELETON OVERVIEW

The Exoskeleton structure resides on the dorsal side of the hand and the forces are applied from that direction. The feedback forces are generated by dc motors mounted in a low profile power pack and are transmitted to the fingers by low friction pull-cables. Measurement of the finger flexion is achieved by a combination of flexible resistive sensors integrated in a soft lycra glove and custom made linear electromagnetic sensors embedded in the exoskeleton's metallic structure. The system is designed for later integration of Hall effect sensors for accurate measurement of adduction and abduction angles of the three fingers. The incorporated glove unlike other systems is part of the exoskeleton structure and thus it is faster to put on and take off. The design also allows for fast adjustment of the exoskeleton for different hand sizes. Patient safety is provided by mechanical stops that limit the finger motion to within acceptable range in case of exoskeleton loss of control.

This haptic system is a single wearable device although it can be visualised as 3 main modules, figure 1. These are: 1) The exoskeleton, that consists of the hand support plate and the aluminium structure that helps to transmit the feedback forces to the finger joints, 2) the glove unit and 3) the Power pack.

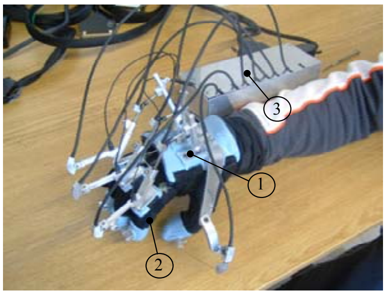



Figure 1. The hand exoskeleton indicating the three basic modules.

### A Mechanical Design

The exoskeleton developed provides force feedback to the index, middle and ring fingers and to the thumb. For the first three fingers force feedback is provided for their proximal and distal phalanxes while for the thumb only the distal phalanx is currently active. The exoskeleton is designed to fit a range of hand sizes and for this purpose it incorporates adjustment levers that allow fast and easy adjustment of the metallic structure for the three fingers. A 3D Cad drawing of one finger is presented in Figure 2.

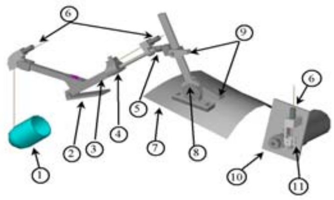


Figure 2. Main components of the exoskeleton: 1-Finger Cup, 2-metalic plate attached with Velcro to the proximal phalanx,3-Structure for support and finger flexion measurement, 4-Steel rod & linear bearing, 5-Universal Joint, 6-Pull cables for force transmission , 7-Cushioned thermoplastic plate for exoskeleton support on the hand, 8-Adjustable Support, 9-Adjustment levers , 10-Motor module, 11-Strain gauge for measurement of force applied to the fingers.

The design of the exoskeleton structure that attaches to the proximal phalanx serves several purposes. Firstly a second degree of force feedback is applied to the finger by means of the pull cable acting on the linear joint. This creates a vertical force component to this phalanx and secondly it directs the force applied by the string to the fingertip, figure 3. As the finger flexes, the direction of the fingertip relative to the horizontal changes from 0° to approximately 150°. With the aid of figure 3 it can be visualised that if the exoskeleton structure was horizontal and fixed e.g. point O, then for large bending angles the finger distal knuckle would collide with the string. Thus the mechanism shown is used to provide some correction to the direction of the force applied. In addition, this structure provides a rigid mounting point to the pull cable acting on the distal joint. The connection with the linear DoF to the support plate is necessary in order to counterbalance internal forces generated due to the tension force on the string between the fingertip and the exoskeleton. An analysis of the relevant forces acting in the system will be presented in a following section. The finger exoskeleton structure is securely attached on the glove so that the user only has to tighten the velcro straps that hold it firmly on the finger. This reduces the effort and time needed to wear the device. The exoskeleton can be relatively quickly adjusted for different users that do not have extremely different hand sizes. This is achieved by means of the levers, figure 2. If the device has been adjusted to a particular user before, then the time needed to fit it is about 1min.

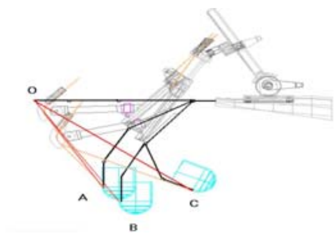



Figure 3. Different finger flexion positions and the respective position of the string relative to the finger. Lines OA, OB and OC indicate the position of the string as it would emerge from a straight exoskeleton structure

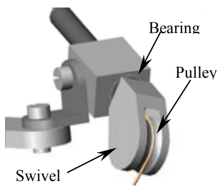



Figure 4. Thumb mechanism ensuring correct direction of the force and small transmission friction .

The thumb exoskeletal structure consists of a metallic extension and a cable attachment at the end of which there is a specially designed swivel that always directs the string in the direction of the thump's tip, figure 4. This structure ensures correct force direction and low transmission friction. In order to simplify the design the thumb has only one actuated DoF.

*B Hand Gesture information*

The coordination of the feedback signals during physiotherapy exercises requires the ability to accurately monitor the patient's hand motions and successfully extract the hand gesture information. To address this requirement the hand exoskeleton employs a combination of input sensors.

As mentioned previously the exoskeleton incorporates a lycra glove. This glove unit forms the housing of seven resistive bend sensors that measure finger flexion. Four of them measure the flexion angle of the middle joints of the four fingers and three the flexion, rotation, abduction and adduction of the thumb. These sensors are securely placed on top of their associated joints with one of their ends secured on the fabric while the other end is free, conforming tightly on the dorsal side of the finger's joints.

The angle $\theta_3$ of the distal joint is calculated from the middle joint angle $\theta_2$ measured by a bend sensor [9].

$$\theta_3 = 0.46 \cdot \theta_2 + 0.083 \cdot \theta_2^{\,2} \tag{1}$$

Because of the mechanical structure placed on the top of the hand and the proximal phalanxes, the flexion measurement of the proximal joint is not performed with bend sensors. Instead a custom made linear electromagnetic sensor was employed that was embedded in the metallic structure, figure 5. This sensor is a 40mm

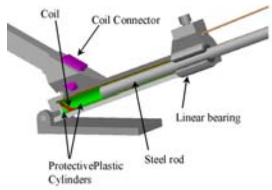



Figure 5. Linear electromagnetic sensor integrated in the metallic structure.

stroke custom designed linear variable transformer that measures the movement of a steel rod moving within the core. This provides an indirect measurement of the angle $\theta_1$ since it measures the length *l*, figure 6. From the geometry of the system, figure 6, given the known lengths $l_1$, $l_2$, $l_3$ and *m*, the angle $\theta_1$ can be computed as a function of the measured length *l*.

From figure 6 the following equations that describe the system can be extracted.

$$\theta_1 = \theta - (180 - \sigma) \tag{2}$$

$$\theta = \cos^{-1}\left(\frac{n^2 + m^2 - \ell^2}{2 \cdot n \cdot m}\right), \sigma = \cos^{-1}\left(\frac{\ell_3^{\,2} + n^2 - \ell_2^{\,2}}{2 \cdot \ell_3 \cdot n}\right) \tag{3}$$

$$n = \sqrt{\ell_2^{\,2} + \ell_3^{\,2} - 2 \cdot \ell_2 \cdot \ell_3 \cdot \cos^{-1}\rho}\ , \ \rho = 180 - (\upsilon + \omega) \tag{4}$$

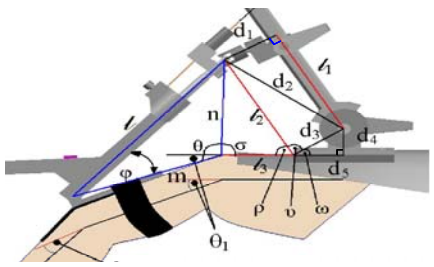


Figure 6. Model of the finger-exoskeleton system for the derivation of the kinematics equations.

The angles $\upsilon, \omega$ can be computed using simple geometry

$$\upsilon = \cos^{-1}\left(\frac{\ell_2^{\,2} + d_3^{\,2} - d_1^{\,2} - \ell_1^{\,2}}{2 \cdot \ell_2 \cdot d_3}\right), \omega = \tan^{-1}\left(\frac{d_4}{d_5}\right) \tag{5}$$

C *Actuation*

Actuation in the hand exoskeleton is provided using seven dc motors. Forces generated by the motors are transmitted from the actuator site to the finger segments using a cable transmission system. For the purpose of force control the system utilises strain gauge based force sensors located at the motor site figure 7. With this method the force applied by the motor is measured and forms the feedback signal of the finger force control loop.

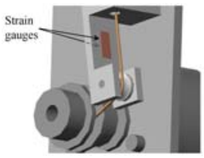
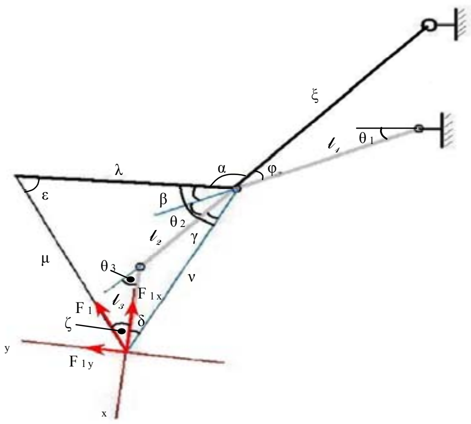



Figure 7. Strain gauges mounted on for force measurement

## III FINGER FEEDBACK FORCE ANALYSIS

To accurately control the forces applied to the finger segments the equations relating the forces generated by the actuators and those exerted at the finger point through the hand exoskeleton structure need to be derived. Figure 8 presents an analysis of the force acting on the fingertip. The force $F_1$ applied by the motor can be analysed into two components, one acting vertically to the distal phalanx and another acting horizontally. As only the $F_{1y}$ component contributes to the constraining of the finger flexion it is important to calculate the relationship between $F_{1y}$, and the force $F_1$. Decomposing $F_1$ on the xy Cartesian axes system shown above we can write:

$$F_1 = \frac{F_{1y}}{\sin\zeta} \tag{6}$$




F

igure 8. Analysis of forces at the distal segment

From the triangle with sides $\lambda$, $\mu$, $\nu$ the following can be derived:

$$\zeta = \cos^{-1}\left(\frac{\mu^2+\nu^2-\lambda^2}{2\cdot\mu\cdot\nu}\right)-\delta\,,\ \mu=\sqrt{\lambda^2+\nu^2-2\cdot\lambda\cdot\nu\cos\kappa} \tag{7}$$

$$\kappa=\beta+\theta_2+\gamma\,,\ \beta=180-\alpha-\varphi \tag{8}$$

Where $\varphi$ is derived from figure 6 and $\alpha$ is known structure parameter.

$$\varphi=\cos^{-1}\left(\frac{\ell^2+m^2-n^2}{2\cdot\ell\cdot m}\right) \tag{9}$$

$$\gamma=\cos^{-1}\left(\frac{\ell_2{}^2+\nu^2-\ell_3{}^2}{2\cdot\ell_2\cdot\nu}\right) \tag{10}$$

Also for the triangle with sides $l_2$, $l_3$, $\nu$ we have:

$$\delta=\cos^{-1}\left(\frac{\ell_3{}^2+\nu^2-\ell_2{}^2}{2\cdot\ell_3\cdot\nu}\right) \tag{11}$$

$$\nu=\sqrt{\ell_2{}^2+\ell_3{}^2-2\cdot\ell_2\cdot\ell_3\cos(180-\theta_3)} \tag{12}$$

Due to the mechanical structure of the exoskeleton the force $F_1$ applied at the fingertip is not completely isolated from the rest of the finger. This is because the structure strapped at the proximal phalanx can rotate about the universal joint, point A in figure 9, due to $F_1$. It also behaves like a lever and creates an undesirable force $F'$ at the middle joint, point B. In figure 9 large headed arrows indicate forces on the finger while small headed arrows indicate forces on the exoskeleton.

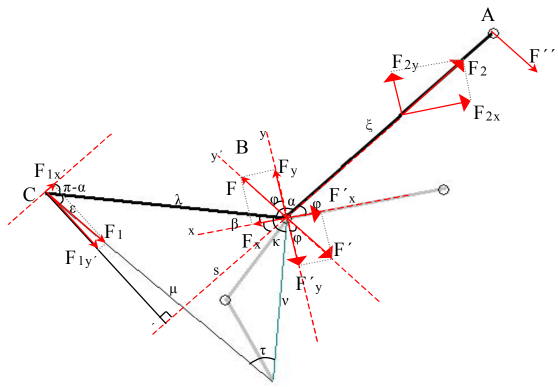



Figure 9. Analysis of forces exerted at the proximal segment.

We start the analysis of the forces exerted at the finger segments by initially considering only the force acting at the distal segment of each finger. There are three forces acting on the exoskeleton structure $F_1$ (the string tension of the distal joint ), $F$ (the reaction of $F'$ on the structure) and $F''$ the balancing force from the universal joint, point A. $F$ can be found by calculating the moments of the forces acting on the angled structure, about point A, at the equilibrium state. In the equilibrium the equation that describes $F$ is:

$$F=\frac{F_1\cdot\sin(\alpha+\kappa+\tau)\cdot(\xi-\lambda\cdot\cos\alpha)}{\xi} \tag{13}$$

Since $F'$ is the opposite of $F$ we can write:

$$F'=-F \tag{14}$$

From the analysis above it is clear that force, $F_1$, applied at the distal segments of each finger generates, due to the exoskeleton mechanical structure and way of support, additional force components $F'$ at the proximal segment. These components are unwanted and directly create a false sensation at the proximal phalanx. To minimize this effect a force $F_2$ acting at the linear joint of the exoskeleton can be used.

From figure 9 the force applied by the motor at the linear joint of the exoskeleton $F_2$ creates a force $F_{2y}$ at the finger's proximal joint, which can be related to the string tension force as follows:

$$F_{2y} = F_2 \cdot \sin\varphi \tag{15}$$

This component $F_{2y}$ can be used to provide some compensation to $F'_y$, figure 9.

## IV SYSTEM CONTROL

The control of the hand exoskeleton unit is realized using a dedicated PC. The control PC is responsible for the data acquisition of the input and cable tension sensors of the hand exoskeleton unit and for the execution of the control scheme that enables accurate rendering of the simulated grasping forces generated during the execution of the hand therapy regimes, figure 10.

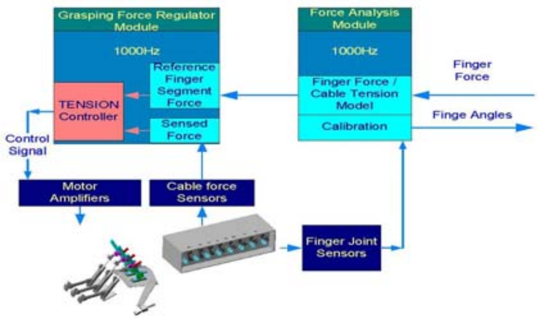
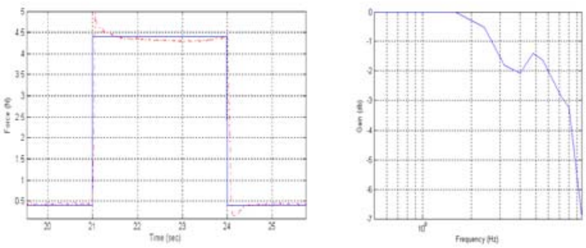



Figure 10. Hand exoskeleton control.

Figure 11 demonstrates typical step and frequency responses for one of the exoskeleton finger joint.



(a) (b)

Figure 11. Typical (a) Step Response, (b) Frequency response of a hand exoskeleton joint

The main software running on the dedicated PC can be divided into two main modules. The first module named the Grasping Force regulator module is responsible for the control of the cable tension for each of the seven cable transmission systems. Using the feedback provided by the cable tension sensor on each force transmission cable, a tension control loop has been formed around each individual cable. The actuator control signal computed using a classic PID control law:

$$u = K_{pr} \cdot e + \frac{1}{T_i}\int e + T_d \cdot \dot{e} \quad \text{where } e = \tau_d - \tau_s \tag{16}$$

is the cable tension error. The reference to the Grasping force regulator module comes from the Force Analysis module. This module is responsible for two tasks. The first task is to generate the required reference tension from the simulated grasping force using the Force analysis described in section III. The second task is the signal processing and calibration of the finger joint angles. Force and joint angle data are exchanged with the virtual simulation through this module.

## V. HAND THERAPY SYSTEM/EXPERIMENTAL RESULTS

To enable the execution of hand therapy exercises the system described in the previous sections was integrated within a Hand Therapy System. This therapy system, which is shown in figure 12 formed the test-bed where a clinician can customise and perform both finger motion evaluation tests and hand therapy regimes. The later resemble real tasks as much as possible particularly in terms of mechanical movements. The Hand therapy system consists of the Virtual Hand Therapy Station (VHTS) and the Hand exerciser Server (HES). The VHTS consists of a dedicated graphics machine that is responsible for the execution of the software relating to the exercise customisation and visualization. The HES is realized using a dedicated PC, which executes the software modules associated with the Hand Exerciser device calibration and control described in section IV. Communication between the (VHTS) and (HES) is performed using a dedicate TCP/IP link. The aim of the Virtual Hand Therapy system is to perform hand rehabilitation using simple tasks. Since the exact type of deficiency can vary tremendously from patient to patient, even with the same diagnosis, the system was designed to be flexible so that the training can be adjusted to the needs of different patients. The virtual exercises resemble the real tasks as much as possible with the care that very complex, realistic or fanciful graphics and fast-paced game formats may be overwhelming for patients. In contrast, a very simple display, with few movements may help a patient to focus on the task at hand and enhance learning.

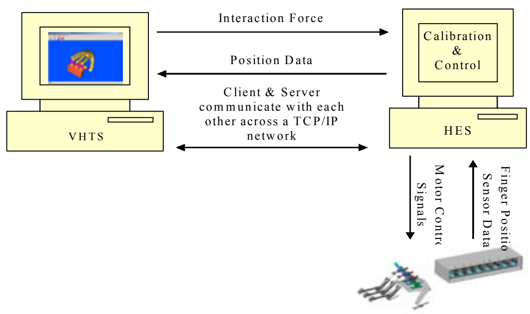
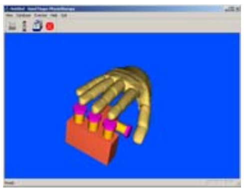


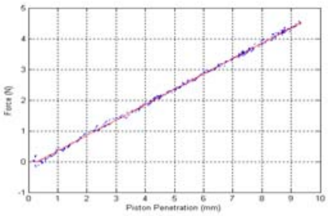

Figure 12: Hand Therapy System Configuration

In this respect existing therapy regimes constitute the basic principles in designing the VR physical exercises. Based on these existing physiotherapy methods recommended by physicians, three initial exercise regimes were developed, figure 13.

The first two figures 13a and 13b imitate the action of existing Thera-band and the Deluxe band exercisers [18] in the virtual environment figure 14a and 14b. The aim of these exercises is to strengthen grip and increase hand motion. In the third exercise figure 13c the patient is required to push down the virtual model of a trumpet key.

(a) (b)






(c) (d)

Figure 13. Implemented Hand Therapy Virtual Exercises for Finger fractionation and strength.

(a) (b)

Figure 14 Thera-Band, Deluxe Hand Exercisers

In order to do so, the patient must resist the opposing force of the virtual spring in the piston and flex his fingers. The stiffness of the spring is increased as the patient's therapy progresses. Figure 13d shows the trajectory of the force experienced by the user's finger during the compression of the trumpet key piston. The stiffness of the virtual piston was 500N/m.

## VI. CONCLUSIONS AND FURTHER WORK

The overall aim of this project was to provide physiotherapy regimes in an interactive virtual environment using a hand exoskeleton based exerciser.

As far as the therapeutic functionality of this system is concerned it provides facilities for hand motion tracking, recording and analysis as well as ability of execution of both occupational and physical therapy exercises. The mechanical structure of the hand exerciser provides 7 active degrees of freedom. Finger motion tracking is performed using a mixture of different sensors while finger force reflection that is generated by DC motors is accurately controlled by means of strain gauge based sensors.

The hand exerciser was integrated within a Hand Therapy system, which enables a clinician to customise and perform hand exercises and finger motion evaluation tests. Although, the experiments were performed by healthy subjects, they indicated that the system has the potential to be used as a possible adjunct to conventional physiotherapy.

Further work will incorporate improvements both in structural and functionality aspects of the system as well as in software and therapy specific issues. Some of the more immediate developments foreseen are listed below.

i) The integration of additional input sensors (Hall effect) to enable accurate measurement of the finger proximal joint adduction-abduction motion.
ii) The provision of force feedback for the distal joint of the little finger and the incorporation of one additional force feedback degree for the thumb adduction abduction motion.
iii) Incorporation of additional exercises to train other finger parameters such as speed and range of motion.
iv) The execution of a full clinical study using the hand finger physiotherapy system to facilitate recovery in patients with hand impairment.
v) The hand finger physiotherapy system can be further extended to include tele-rehabilitation capabilities.

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