Development and evaluation of a haptic framework supporting telerehabilitation robotics and group interaction

A thesis submitted for the degree of Doctor of Philosophy

by

Hoang Ha Le

Abstract

Telerehabilitation robotics has grown remarkably in the past few years. It can provide intensive training to people with special needs remotely while facilitating therapists to observe the whole process. Telerehabilitation robotics is a promising solution supporting routine care which can help to transform face-to-face and one-on-one treatment sessions that require not only intensive human resource but are also restricted to some specialised care centres to treatments that are technology-based (less human involvement) and easy to access remotely from anywhere. However, there are some limitations such as network latency, jitter, and delay of the internet that can affect negatively user experience and quality of the treatment session. Moreover, the lack of social interaction since all treatments are performed over the internet can reduce motivation of the patients. As a result, these limitations are making it very difficult to deliver an efficient recovery plan.

This thesis developed and evaluated a new framework designed to facilitate telerehabilitation robotics. The framework integrates multiple cutting-edge technologies to generate playful activities that involve group interaction with binaural audio, visual, and haptic feedback with robot interaction in a variety of environments.

The research questions asked were:

1) Can activity mediated by technology motivate and influence the behaviour of users, so that they engage in the activity and sustain a good level of motivation?
2) Will working as a group enhance users' motivation and interaction?
3) Can we transfer real life activity involving group interaction to virtual domain and deliver it reliably via the internet?

There were three goals in this work: first was to compare people's behaviours and motivations while doing the task in a group and on their own; second was to determine whether group interaction in virtual and real

environments was different from each other in terms of performance, engagement and strategy to complete the task; finally was to test out the effectiveness of the framework based on the benchmarks generated from socially assistive robotics literature. Three studies have been conducted to achieve the first goal, two with healthy participants and one with seven autistic children. The first study observed how people react in a challenging group task while the other two studies compared group and individual interactions. The results obtained from these studies showed that the group interactions were more enjoyable than individual interactions and most likely had more positive effects in terms of user behaviours. This suggests that the group interaction approach has the potential to motivate individuals to make more movements and be more active and could be applied in the future for more serious therapy. Another study has been conducted to measure group interaction's performance in virtual and real environments and pointed out which aspect influences users' strategy for dealing with the task. The results from this study helped to form a better understanding to predict a user's behaviour in a collaborative task. A simulation has been run to compare the results generated from the predictor and the real data. It has shown that, with an appropriate training method, the predictor can perform very well.

This thesis has demonstrated the feasibility of group interaction via the internet using robotic technology which could be beneficial for people who require social interaction (e.g. stroke patients and autistic children) in their treatments without regular visits to the clinical centres.

Declaration

I hereby confirm that this is my own work. All the resources and material from other sources have been cited accordingly.

Hoang Ha Le

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Glossary of Abbreviations

ABI	Acquired Brain Injury
AI	Artificial Intelligence
ANN	Artificial neural network
APT	American Physical Therapy Association
AR	Augmented Reality
ATRA	America Therapeutic Recreation Association
BMP	Basic metabolic panel
BOS	Base of support
BWSTT	Body weights and a treadmill training
CAMR	Computer-assisted motivating rehabilitation
CEC	Constant error carousel
CNS	Central nervous system
COM	Centre of mass
CVA	Cerebrovascular accident
DAFS	Direct Assessment of Functional Status
DLA	Daily life activities
DOF	Degrees of freedom
EMG	Electromyogram
FDLA	Fundamental daily life activities
fMRI	Functional magnetic resonance imaging
FMS	Functional mobility skills
FNN	Feed-forward neural network
FIM	Functional independence measure scores
FSR	Force-sensing resistors
GSR	Galvanic Skin Response
HEP	Home exercise program/ Home workout program

ICF	International Classification of Functioning, Disability, and Health
IDLA	Instrumental daily life activities
KP	Knowledge of performance
KR	Knowledge of results/ understanding of outcomes
LE	lesser extremity
LM	Levenberg-Marquardt
LSTM	Long Short-Term Memory
MAS	Multi-agent systems
MS	Multiple sclerosis
NARX	Nonlinear Autoregressive models with exogenous input
NMSE	Normalised mean squared errors
OSC	Open Sound Controller
PET	Positron emission tomography
POC	Plan of care
QOL	Quality of life
RMTP	Reliable Multicast Transport Protocol
RNN	Recurrent neural network
SAR	Socially assistive robotics
SCI	Spinal cord injury
SCTP	Synchronous Collaboration Transport Protocol
SRM	Scalable Reliable Multicast
SRTP	Selective Reliable Transmission Protocol
TBI	Traumatic brain injury
UE	Upper extremity
ULR	Upper Limb Rehabilitation
VR	Virtual reality
WCPT	World Confederation for Physical Therapy
WHO	World Health Organisation

WBAN   Wireless body area network

Chapter 1: Thesis Overview

Chapter 1 introduces the research problem, the need of this research, the hypotheses, studies conducted to test out these hypotheses, the research methodology and presents the structure of this thesis.

1.1 Problem statement

Institutions in healthcare face the strain of a significantly larger older adult population (Calvaresi et al., 2016). A longer life expectancy is naturally met by increasing demand for medical and technological contributions to extend "good-health" and disability-free period. The primary factor catalysing the older adult impairing process is the progressive reduction of mobility and activity, and the increased susceptibility to disease, the high impact falls and bone fractures (Buonocunto et al., 2018). Although less-invasive surgical techniques are emerging, post-intervention rehabilitation often involves extended periods of bespoke therapies.

Traditional rehabilitation increases public-health costs and, in some cases, due to a lack of resources, reducing the quality of the recovery. Therefore, finding a solution to simplify the access to health services can help to balance the quality of care and the increasing numbers of patients (Cesarini et al., 2015). For instance, a system that can automatically transmit the patients' data collected from the local areas to the health institutions can benefit patients who require continuous or selective monitoring (Hailey et al., 2011; Dubovitskaya et al., 2018). Traditionally, telemonitoring is a self-contained practice limited to passively observing the patients, the need for remote sensing is crucially coupled with the need for coaching older adults in their daily living. Critical activity such as telerehabilitation requires telemonitoring not to be limited to observing patient behaviours. Indeed, patient adherence and acceptability of rehabilitative practices need to be actively enhanced, overcoming pitfalls due to motor (e.g., endurance), nonmotor (e.g., fatigue, pain, dysautonomic symptoms, and motivational), and cognitive deficits. Patients, physiotherapists, and health institutions can gain numerous benefits from an extensive adoption of telerehabilitation systems. Telerehabilitation combining with robotics technology is mostly known for providing treatment for patients who need physical rehabilitation (e.g., patients after stroke) due to the nature of robots that can be controlled remotely to generate intensive and repetitive practice.

However, by creating group activity, robotic telerehabilitation could also have the potential to help people with social disability (e.g., autistic people).

Stroke is the fourth most common cause of death in the UK and the third-most in the US and a leading cause of disability, especially for the older adults (UK National Stroke Association, 2017; American Stroke Association, 2019). Most patients could survive after their first stroke (Langhorne et al., 2011); however, 70-85% of them will experience hemiplegia (the paralysis of one side of the body) affecting their daily activities (Dobkin, 2004). The annual incidence of stroke ranges from over 100,000 people in the UK, 800,000 in the USA, to 15,000,000 worldwide (UK National Stroke Association, 2017). Approximately a third of people surviving after stroke have severe disabilities (Abrams & Berkow, 1997).

The literature states that the combination of conventional physiotherapy and robot-mediated therapy can enhance stroke recovery progression (Amirabdollahian, 2003; Fazekas et al., 2004; Loureiro et al., 2009). The uses of robot technologies in several areas, including neurorehabilitation, have risen rapidly since 1990 (Loureiro & Harwin, 2007).

Over the last decade, the use of robots for rehabilitation has prompted with opportunities to create and deliver complex therapies that would be too difficult or demanding for a human therapist to perform. Besides, the added value is that robotic rehabilitation can provide the opportunity for the therapist to observe the whole process of physiotherapy to make better decisions on the therapy paradigm to be used with the patient (Loureiro & Smith, 2010).

Although there is no question as to the benefits of robotic technologies in neurorehabilitation for patients after stroke, there still exists a need to tailor and optimise the current robotic rehabilitation systems. A crucial aspect is that the system should be portable and therefore facilitate its usage in an unsupervised environment such as the home.

Post-stroke patients might be returning home sooner than in the past due to the shortening of hospital stays (Maureen et al., 2005). Consequently,

they have a significant need to continue their rehabilitation process at home. In order to do so, a robot-aided system which allows the therapist to provide rehabilitation remotely could be a solution. The system does not only reduce the burden of the patient's family but also benefits patients who cannot access the rehabilitation centre due to limited transportation. However, the critical issue of such a system is to maintain the patient's motivation since they might feel isolated because of the lack of interaction between them and other patients as well as with the therapist. Therefore, the system must also have frequent social interactions between patients and therapists. A telerehabilitation system like that is also needed for people who require to improve their social interaction skills, for example, people with autism.

Autism is a lifelong condition affecting the lives of thousands of people in the UK. People with autism usually have limitations with social and communication abilities; hence, they may depend on specialist support throughout their lives. It is believed that early intervention through playful activity may be useful in improving social communication and interaction skills (Rogers et al., 1998). However, treatment for autism is usually very costly for autistic children and their families when accessible (Tarkan, 2006). Due to the lack of personnel/equipment in the clinic and the cost of autism intervention, it is safe to say that autistic children have a similar need as post-stroke patients: a better assistive tool that enables them to have intensive treatment at home or other social environments outside of the clinic. As a result, they have the same challenge as post-stroke patients to maintain the motivation to follow therapeutic exercises.

A new robotic field called socially assistive robotics has the potential to address this challenge of both populations (post-stroke patients and autistic children) since this field mainly focuses on the development of social interaction to enhance user's engagement. The field itself, however, is still at the early stage of development therefore it requires much more research to have a better understanding of the field in general, e.g., investigation on different environmental settings such as therapy centre, hospital, schools,

private home, etc.; or study on how to enhance robot's actions to adapt user's behaviours accordingly (Tapus et al., 2007)

Haptic interfaces are a particular group of robots that can provide safe interactions for humans. They can also enhance the user's experience through kinaesthetic feedback via the sense of touch (tactile) or force feedback (proprioceptive) while interacting with virtual objects. It has been shown that virtual reality (VR) - haptic based systems can motivate and encourage patients to follow the physiotherapy process for longer periods (Broeren et al., 2006; Loureiro et al., 2003). By combining cutting-edge haptic interfaces and VR technology, it is possible to create an immersive robot-mediated system for neurorehabilitation. The majority of these interventions have been developed to assist people with physical impairments. Exciting new approaches, such as the use of a haptic robot for assisting in a social context, focuses on promotion of attention and engagement to the therapeutic regime through group interaction even with limited physical contact between the user and the robotic counterpart.

However, this approach requires travelling to a specialist centre and often not available for those living in remote locations. To account for this, the next step would be to make such interventions available remotely perhaps through a VR environment via a network connection. The benefits of such a telerehabilitation system include: reducing transportation cost and time, motivating patients to exercise frequently in the comfort of their homes, daily checking, and enhancing current therapies.

1.2 Hypotheses

It is known that motor skill can be learned through practice, thus increasing the amount of practice can enhance skill learning. However, there is limited information on how to design engaging tasks to encourage people to spend more time to practice, especially when it comes to social environments outside of the hospital. This thesis focuses on understanding how people, by using a robotic/ haptic interface, interact with each other in different social scenarios. For example, while engaging in therapy alone and/or in a group with varying interaction and communication levels, such as talking to a human agent in a real versus virtual environment. It is envisaged that such interactions would enable the possibility of bringing the rehabilitation therapy from hospital to home or other social environments.

Central Hypothesis: Central Hypothesis: Novel technologies mediated by social interaction can positively influence participants' interactions and engagement levels. By using those technologies, a real-life task involving social interaction can be transferred to a virtual domain and delivered remotely.

The literature suggests that during the learning/ re-learning of new/ forgotten motor skills, a high level of attention and engagement can help to induce cerebral plasticity after neurological impairments (Fisher & Sullivan, 2001). Several groups have tried different strategies to maintain participants' attention and engagement in the past. However, it is very little known in the literature regarding how participants interact and their behaviours during playful activities when working as groups or individually. Moreover, there is a need to deliver collaborative activities in a virtual environment and via internet connection. Therefore, a model to predict participants' behaviours is necessary to maintain a smooth interaction in a collaborative task that involves a robot-mediated virtual environment. This hypothesis was tested by conducting three different experiments inclusive of healthy participants and one experiment involving children with autism.

It is anticipated that the stroke population will enjoy the environment in the same way as the tested populations due to the fun factor of the activities. In detail, this central hypothesis was devised to two sub-hypotheses:

Hypothesis 1: Playful interaction in a group modulated by a haptic interface will enhance engagement and motivation. As a result, participants will spend more time on the same task than they do individually.

It is based on the fact that motor interactions between humans are the foundation of all types of social behaviours (Clark, 1996)

This hypothesis was tested by conducting studies involving participants (healthy people and autistic children) doing the same playful and interactive activity in a group and on their own. The results extracted from those studies would help to identify any difference between a group and individuals.

Hypothesis 2: Collaborative behaviours can be effectively predicted from data collected from pairs of individuals using a haptic interface and the outcome of such prediction should be close to the real interaction.

For a collaborative task with a specific goal hence the user's behaviour is predictable, it is anticipated that an AI agent trained from participant's kinetic and kinematic data can perform well and close to the human counterpart. The discussion information between participants is not needed and does not affect the performance of the AI agent (even though communication is very crucial for the participants to complete the task successfully when they work with real human).

This hypothesis was tested by collecting the data in both real and virtual worlds to investigate further how environments and conditions could affect the quality of interactions between participants. The collaborative task required participants to work in pairs to complete. Two different conditions were devised for the participants while performing the task: with or

without communication (allowed and not allowed to talk to each other). These two conditions were used to test the importance of communication when two participants work together to finish a collaborative task in a virtual environment. The collected data was put into AI training using different machine learning algorithms. The results were compared between the training methods and real data.

1.3   Research methodologies and analyses

In order to test out the application of the developed framework and stated hypotheses, both quantitative and qualitative research methods were used.

The first study conducted with a robotic bell was designed to probe how group interactions would affect people's behaviours by reshaping the individual's mental model (Chapter 6 – section 6.1). The task was generated by the developed framework (Chapter 5) and had a specific goal without explicit instruction to complete. Qualitative (observation) and quantitative data (time to complete the task and numbers of movement) were extracted from eight healthy participants. The analysis implied that working in a group would reshape their individual's mental model formed from the previous task, and group interaction task was engaging for the users, thus encourage them to make as many movements as possible.

The second study (Chapter 6 – section 6.2) examined interactions with a sonic and haptic painting with healthy participants with an emphasis on determining the difference between individual and group interactions in the same task. The task was explorative and, therefore, had no specific goal or instruction. Qualitative (observation) and quantitative data (time to spend on the task, velocities of the movement, numbers of time when participants touched the virtual objects, and questionnaires) were extracted from thirty-six participants. Furthermore, for a better comparison of individual and group interactions, t-tests have been done. The empirical results showed that group interactions were more engaging (e.g. participants spent more time on the task which implied that they wanted to

explore more and made much more movements) comparing to individual interactions.

In order to investigate further whether the approach of sonic and haptic painting as well as group interaction could enhance motivation in people with a neurological disorder, a third study was conducted with autistic children (Chapter 6 – 6.3). The setting, data collection, and analysis were similar to the second study. The results showed the engagements of all participants, and they seemed to be happy doing the task. The results also implied that group interaction had a positive impact on them.

The study in chapter 7 helped understand better how group interaction works to come up with a consensus strategy while completing a collaborative task. The quantitative testing of the proposed approach involved kinematic and kinetic data, and psychophysiological stressors captured using validated intrinsic motivation questionnaires. The qualitative data was collected from observation and interviews. The performance was then evaluated systematically. The analysis conducted in both real and virtual worlds; the t-tests were used to identify differences in performance between two environments.

The data collected from this study has been used to train the system (using two different methods) to predict the user's movements. Results from those two methods have been compared to select the better one, which is closer to the real data (Chapter 8).

1.4 Thesis structure

Chapter 1: Introduction of the thesis. This chapter states the problems this thesis trying to tackle. It introduces the hypotheses and research methodologies as well as the structure of this thesis.

Chapter 2: Motor Control Overview, Motor Learning, and Interactive Behaviours. This chapter reviews motor control and motor learning in the literature. It explains the process of adopting new skills in the brain, the stages and different types of motor learning. It also introduces different types of group interactions based on motor learning. Finally, it describes the corresponding method to evaluate each type of interaction.

Chapter 3: Physical rehabilitation methods. This chapter introduces the current methods that are being used for physical rehabilitation. It also describes the patient/client management procedure from the examination to intervention.

Chapter 4: Overview of Robotic Telerehabilitation Systems and The Effect of Network Failures. This chapter introduces currently available robotic telerehabilitation systems and explains the challenge of future work to improve the developed framework based on the effect of a poor network connection on haptic feedback.

Chapter 5: The Design of Haptic Framework Supporting Socially Assistive Robotics and Group Interaction. This chapter introduces the socially assistive robotics field (which the design of this haptic framework is based on) in general as well as illustrating multiple benchmarks to evaluate a socially assistive robotic system. Moreover, it describes the design of the framework itself and its possible improvements in the future.

Chapter 6: Pilot studies: How Working in a Group Changes User's Behaviours. This chapter reports the designs and results of three pilot studies on how group interaction generated by the framework affects user's behaviours. Each study has its particular goal to determine different aspects of group interaction. The purpose of these studies was to determine the differences between a group and individual interactions, the effectiveness of the haptic software framework introduced in chapter 5, and test out the hypotheses.

Chapter 7: Further study: User's Behaviours While Working in Group: Real Vs. Virtual Environments. This chapter presents a comparison of the user's

performance and engagement in the same task between real and virtual environments. The results from this trial will help to form an adaptive function of the current framework, which enables the robot to predict user's behaviours and adapt itself accordingly for better assistance.

Chapter 8: User's input predictor models applying NARX and LSTM neural networks. This chapter uses the data from the previous study to train the system to adapt to the user's behaviour and predict their movements when the data is lost. Two well-known training methods for predicting data in time series systems have been applied and compared to choose the better one for this particular task.

Chapter 9: Conclusions and Future Work. This chapter summarises the findings of this thesis and explains how results obtained from the trials help to improve the current design as well as explains the contributions and significance of this thesis. It also highlights the direction for future studies that will expand our understanding of the field further.

Chapter 1
Thesis Overview

Chapter 2
Motor control, Motor learning and interactive behaviours

Chapter 3
Physical Rehabilitation Methods

Chapter 4
Overview of robotic telerehabilitation systems

Literature Review

Chapter 5
Design of the haptic framework

Chapter 6
Pilot studies involving group interaction

Chapter 7
Further study: User's behaviours while working in group

Pilot studies

Chapter 8
Modelling user's input prediction

Chapter 9
Conclusions

Figure 1.1: Chart illustrates the structure of this thesis.

1.5 Publications

H.H. Le, M.J. Loomes, R.C.V. Loureiro, "*AI Enhanced Collaborative Human-Machine Interactions for Home-Based Telerehabilitation*". 2021 Journal of Rehabilitation and Assistive Technologies Engineering. (Manuscript accepted).

H.H. Le, M.J. Loomes, R.C.V. Loureiro, "*User's behaviours in a collaborative task – real vs. virtual environments*". 2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BIOROB).

H.H. Le, M.J. Loomes, R.C.V. Loureiro, "*Mapping arm movements to robotic sonic interaction promote group dynamics and increase engagement at a task*", International Conference on Neurorehabilitation (Toledo, Spain, 2012), pp. 843–846

H.H. Le, R.C.V. Loureiro, F. Dussopt, N. Phillips, A Zivanovic, M.J. Loomes, "*A haptically enhanced painting as a tool for neurorehabilitation*", 2013 IEEE International Conference on Rehabilitation Robotics (ICORR), vol. 1, no. 6, pp.24-26, June 2013.

H.H. Le, M.J. Loomes, R.C.V. Loureiro, "*Towards Pervasive Motor and Cognitive Rehabilitation Strategies Mediated by Social Interaction*". Converging Clinical and Engineering Research on Neurorehabilitation II: Springer; 2017. p. 369–73.

H.H. Le, R.C.V. Loureiro, F. Dussopt, N. Phillips, A Zivanovic, M.J. Loomes, "*Soundscape and Haptic Cues in an Interactive Painting: a Study with Autistic Children*", 2014 IEEE International Conference on Biomedical Robotics and Biomechatronics (BIOROB), August 2014.

H. H. Le, M. J. Loomes, R. C. Loureiro, "*Group interaction through a multi-modal haptic framework*", IEEE 12th International Conference on Intelligent Environments (IE), pp. 62-67,

Chapter 2: Motor control, Motor learning and interactive behaviours

Chapter 2 aims to provide an understanding of motor control, motor learning and interactive behaviours in human. Before designing any rehabilitation system or framework, it is essential to understand how human can learn their motor skills, what happens inside the human brain to adopt new skills or regain lost skills, how many stages and types of motor learning. It is also important to understand how human interact to each other and their behaviours in motor interaction tasks. Readers with a good knowledge of motor control and motor learning can skip section 2.1 and 2.2.

2.1   Overview of Motor control

Motor learning is essential for human beings since it is required to acquire new skills in real-life, e.g. from simple tasks as reaching or grasping objects to high lever skills as playing sports or instruments. Motor skills are learnt when humans gather sensory information and learn from their own experience to react appropriately, corresponding to the environment changes. The sensory information is crucial since it helps to develop a motor program, which is defined as "an abstract representation that, when initiated, results in the production of a coordinated movement sequence" (Schmidt and Lee, 2011). To be more specific, a motor program can be considered as an abstract set of rules which contains adequate information for coordinated actions. This information, for instance, could be the muscle(s) and limb(s) used in the movements, the forces applied, order and timing of events or the sensory feedback from the corresponding environment(s) and limb(s) (Schmidt and Lee, 2011). A motor plan is a sophisticated motor program that can consist of multiple smaller motor programs for a particularly intentional movement.

Motor memory, i.e. procedural memory consists of different information from learnt motor programs such as (1) initial movement conditions; (2) how the movement felt, looked, and sounded (sensory consequences); (3) specific movement parameters (knowledge of performance); and (4) outcome of the movement (knowledge of results) (Shumway-Cook and Woollacott, 2011). A coordinated movement is the result of the interaction from different systems, not only the nervous systems. For example, such systems could be the musculoskeletal system (body mass, inertia, and gravity), cognition (attention memory, learning, judgment, and decision making) and perception (sensation's interpretation). Therefore, any impairment from these systems can significantly affect the outcome of the movement, reducing the quality and the level of function achieved (Bernstein, 1967). The central nervous system (CNS) is critical to managing task demands (termed task systems). For less demanding tasks, only a small

portion of CNS may be required whereas the entire system may be needed for more complicated tasks. As a result, for some simple movements, the highest level of command may not be necessary. (Bernstein, 1967; American Physical Therapy Association, 2001). Motor movements can be categorised into two types: reflexive (involuntary) and voluntary. However, some movements are mostly involuntary but also subject to voluntary adjustment, e.g. swallowing, chewing, scratching, and walking. Figure 2. 1 shows a general motor control scheme that illustrates the control of voluntary movement.

An idea of movement occurs from the brain and commands for voluntary movement are formed in cortical association areas. The cortex, basal ganglia, and cerebellum work together to plan movements. The cortex then executes movements, and the motor commands from this step are relayed through the corticospinal tracts to the spinal cord as well as from corticobulbar tracts to motor neurons in the brain stem. The feedback information from muscles, tendons, joints, and the skin is provided by the cerebellum to adjust and smooth movements. This information is relayed to the motor cortex and spinocerebellum, which in turn, will project to the brain stem. The rubrospinal, reticulospinal, tectospinal, and vestibulospinal tracts in the brain stem are related to posture and coordination. (Barrett et al., 2010).
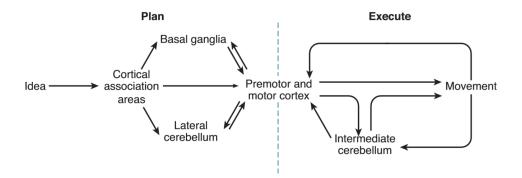
Figure 2.1: Control of voluntary movement. Commands are formed from cortical association areas. The movements are planned in the cortex, the basal ganglia, and the cerebellum. The cortex executes movements, which are relayed to motor neurons via the corticospinal tracts and corticobulbar tracts. The movements are adjusted and smoothed by the feedback provided by the cerebellum. (Adapted from Barrett et al., 2010)

The corticospinal tract is formed by a collection of axons (about 1 million fibres) that carry movement information from the motor cortex to the spinal cord. The lateral corticospinal tract (Figure 2.2) is formed by about 80% of these fibres, which crosses the midline in the medullary pyramids. The ventral corticospinal tract is made up of the remaining 20% of fibres, which does not cross the midline until its destination – the spinal cord.

Lateral corticospinal tract neurons project from cortical areas to the brain stem and make monosynaptic connections to motor neurons that control the groups of skeletal muscles, especially those concerned with skilled movements. There are two types of neurons in the motor system: upper motor neurons and lower motor neurons. Neurons in the cortex and brain stem that travel in the corticospinal tract are upper neurons; they activate the lower neurons, which can make contact with the skeletal muscles to cause muscle contraction.
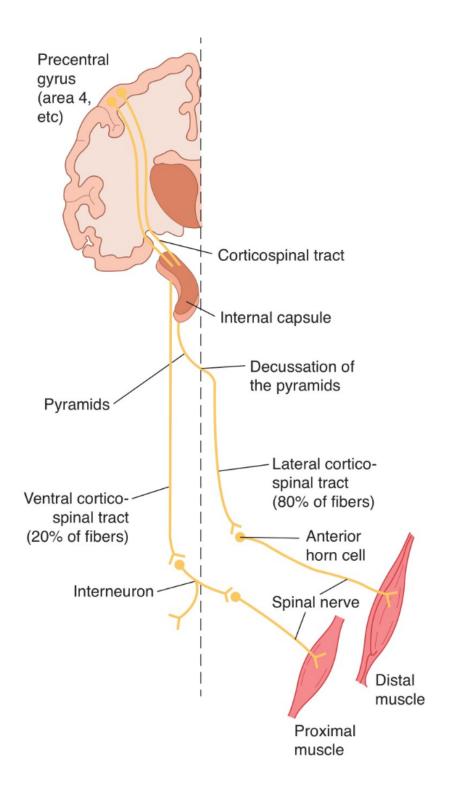
Figure 2.2: The corticospinal tracts. This tract starts from the precentral gyrus and continues through the internal capsule. Most fibres decussate in the pyramids and go down in the lateral division of the tract which can make contact with spinal motor neurons to cause movement. The ventral (or anterior) division of the tract remains

The cortical areas related to motor control is illustrated in Figure 2.3. Approximately 31% of the corticospinal tract neurons are from the primary motor cortex (M1; Brodmann's area 4) whilst about 29% of them are the premotor cortex and supplementary motor cortex (Brodmann's area 6), the rest 40% of them are from primary somatosensory area (Brodmann's area 3, 1, 2) and parietal lobe (Brodmann's area 5, 7)
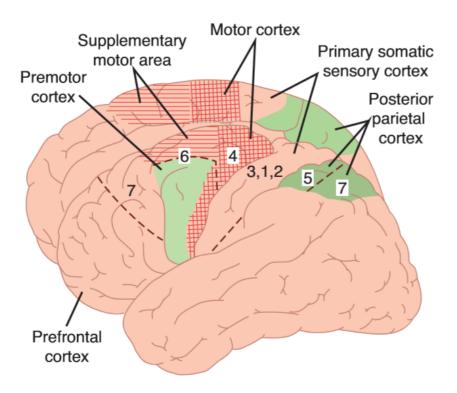
Figure 2.3: Illustration of the human cerebral cortex, showing the cortical areas involved in motor control with the Brodmann's numbers. (Adapted from Principles of Neural Science, 2000)

Positron emission tomography (PET) scan and functional magnetic resonance imaging (fMRI) from a 7-year-old, unanaesthetised, unoperated boy (Figure 2.4) have shown that most of the motor projections are from M1. Figure 2.5 represents the Penfield motor homunculus, which shows the areas in the precentral gyrus dedicated to various parts of the body, with the toes at the top of the cerebral hemisphere and the face at the bottom. The amount of the cortex devoted to each body part is proportionate in size to the complication of motor skill that the part is used on voluntary movement. In other words, the parts that are more complex and have more motor connections (e.g., the hands) are represented as larger in the homunculus than those that are less complex and have fewer motor connections (e.g., the feet).
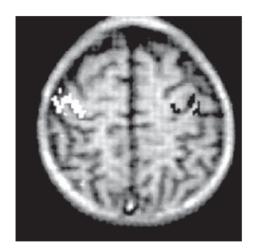
Figure 2.4: fMRI of the hand area of the motor cortex in the human brain when squeezing a rubber ball. Changes recorded when using the right hand are shown in white and with the left hand in black. (Adapted from Waxman, 2003)
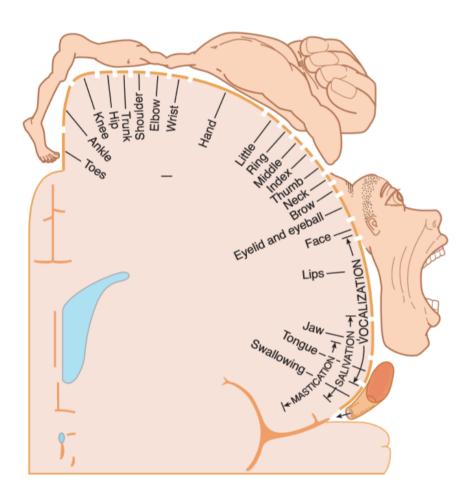
Figure 2.5: Motor homunculus. The figure represents a map of cortical areas dedicated to the various parts of the human body. The size of the parts is proportionate to the amount of cortex devoted to them. (Adapted from Penfield & Rasmussen, 1950)

Figure 2.6 shows the organisation of spinal motor neurons, those locating most medially have the most proximal muscles while those locating more laterally innervate more distal muscles.

Medullary reticulospinal, vestibulospinal, and tectospinal tracts are the medial brain stem pathways that descend in the spinal cord and terminate in the ventromedial area of spinal grey matter to control axial and proximal muscles. The medial tract starts from the medial vestibular nuclei to control neck musculature. The lateral tract starts from the lateral vestibular nuclei and activates motor neurons to control posture and balance.

The rubrospinal tract is the lateral brain stem pathway that starts from the red nucleus (magnocellular part) and terminates in the dorsolateral area of spinal grey matter to control distal muscles.

A Medial brain stem pathways

- Tectum
- Medial reticular formation
- Tectospinal tract
- Reticulospinal tract
- Lateral and medial vestibular nuclei
- Vestibulospinal tracts

B Lateral brain stem pathways

- Red nucleus (magnocellular part)
- Rubrospinal tract
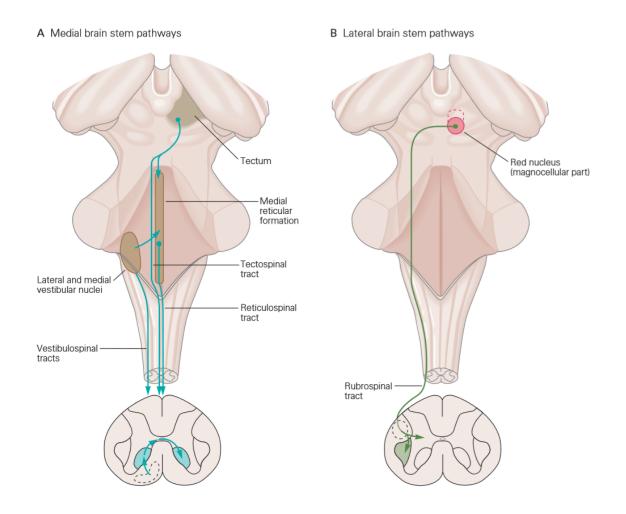
Figure 2.6: Medial and lateral brain stem pathways in motor control.

A) Medial pathways (reticulospinal, vestibulospinal, and tectospinal) descend in the ipsilateral ventral columns of the spinal cord to control axial and proximal muscles. B) Lateral pathway (rubrospinal) originates in the red nucleus (magnocellular part) to control distal muscles. (Adapted from Kandel et al., 2000.)

This section presents what happens inside a human brain when an idea of movement occurs. The next section explains further how new motor skills can be learnt by acquiring and modifying this movement, how patients can recover their lost motor skills, different stages and types of motor learning as well as the measures of motor learning performance.

2.2 Motor Learning

2.2.1 Introduction

Motor learning is a complex process of acquiring and modifying the movement by actions of the CNS. Schmidt and Lee (2011) defined motor learning as "a set of internal processes associated with practice or experience leading to relatively permanent changes in the capability for skilled behavior." The CNS organises and processes sensory information in both serial and parallel manner, the feedback from this information during or after the movement is monitored to generate corrections and coordination – the ability to produce precise, stable, and smooth motor responses.

Motor learning of the patients who lost their movement skills due to injury is different from healthy people. The process of requiring lost skills called recovery of function; this process is based on the fact that the brain has the ability to change and repair itself (termed neuroplasticity). The recovering movements can be either precisely as before or modified depending on the condition of the patient. For instance, with a person with neurological damage, it is usual that the movements are modified and not the same as before. The patient then will need to decide whether the modified movements are sufficient for their daily activities or they will need to adapt to a new strategy to complete the task. For example, a patient after stroke may find it difficult to wear a dress since this task requires upper extremity (UE). A solution for this patient to complete this task is the adoption of new strategies to execute a different group of muscles, which involved less UE to compensate for the loss functions. In this case, the neuroplasticity includes "a continuum from short-term changes in the efficiency or strength of synaptic connections to long-term structural changes in the organization and numbers of connections among neurons" (Shumway-Cook, A. and

Woollacott, M. 2011); in other words, a shift from short-term to long-term memory in the learning processes.

In some cases, the deficits due to CNS damage are very consistent among patients, especially when the effecting areas of CNS are minimal. With more severe cases as patients with traumatic brain injury (TBI), when the damage of CNS is more widespread, the outcome deficits are more complex and look much less apparent on the first examination. Hence it is crucial to monitor and re-examination during the recovery process to understand the patient's capability and deficits.

2.2.2 Stages of Motor Learning

Fitts and Posner (1967) described a model of three main stages in motor learning, which is also supported by Anderson (1982;1995). These stages (cognitive, associated, and autonomous) provide a useful framework for understanding the learning process and developing rehabilitation strategies to improve motor skills.

2.2.2.1 Cognitive stage

In the early cognitive stage, the primary goal is to develop an overall understanding of the task termed cognitive mapping to answer the fundamental decision "What to do." In this stage, the learner is highly dependent on visual feedback to guild the learning and movement. Cognitive processing allows the learner to analyse their abilities and task requirements thus develop a strategy to perform the task. The learner performs an initial trial of the task and tailors themselves during the practice trial. This whole process becomes a trial and error practice while the learner retains some strategies, discards others and refines the movements to select the most reasonably successful strategies. Because the learner develops their strategies and movements from a lot of trials and errors, their improvements in performance can be observed easily during this stage.

2.2.2.2 Associated stage

In the middle-associated stage, the learner already knows the motor patterns; thus, they continue to practice and adjust in order to achieve refinement of the patterns to answer the "How to do" decision. During this stage, unnecessary movements and errors decrease whereas spatial and temporal aspects become organised. The learner's performance of the task improves; therefore, it increases consistency and decreases cognitive activity. The dependence of visual feedback decreases while the proprioceptive cues become more important. The lengths of time of this stage can be varied and can take a very long time, depending on different factors, e.g., the learner's abilities, motivations, level of practice, or simply just because of the nature of the task.

2.2.2.3 Autonomous stage

The final stage is the autonomous phase of motor learning. This stage is just a higher level of the previous stage when the learner keeps practising to have better motor pattern refinements. However, the practice requires very little attention since the motor programs are already too refined that they can almost run themselves (hence termed "autonomous"). The spatial and temporal components are highly organised, and task performance level is very high, with movements are almost error-free (e.g., skilled athletes). At this stage of learning, the learner has time to concentrate on other aspects such as to think about "How to succeed" at their goal (e.g., sports competition).

The strategies of motor learning for patients with brain injury (e.g., post-stroke patients) are entirely different. Some tasks and movements that have been learnt easily before can become extremely challenging now. The lengths of time for patients to stay in each stage mentioned above can be much longer, and their abilities to learn as well as performance is greatly reduced due to the impairments in motor control. Nowadays, it is not rare to see patients being discharged from the hospital, even before completing

their rehabilitation program. As a result, their lost skills have not been re-learnt and refined. The maximum stage that most of the patients can reach is the middle or associated stage.

2.2.3 Measures of Motor Learning Performance

O'Sullivan et al. (2014) introduced six different methods to measure motor learning performance: performance observations, retention tests, transfer tests, adaptability, resistance to contextual change, and active problem-solving.

2.2.3.1 Observations

Observation is one of the most common and traditional methods to measure motor learning performance. Progress in performance during practice is recorded to evaluate motor learning.

Performance requirements are examined for comparison to determine the learning outcomes. For example, a person after stroke can show some independence in motor function after several exercise sessions. A scoring system (e.g., functional independence measure (FIM) scores) is handy to identify changes in the quantity of assistance required. Qualitative changes in performance, when weighed against the criterion skill, can also be employed to record motor learning. Therefore, enhanced coordination in movement implies an improvement in the temporal and spatial organisation. The therapists can report the rate and type of errors (constant/variable) through an error scoring method, which can be applied for a specific training session or across all the training sessions, thus, to record the reliability of the movement. A reduction in the frequency of errors usually implies that there is an improvement in learning. However, this can only be considered as indirect evidence and need to be examined more carefully. For instance, one measurement that is common in skill learning is a trade-off of speed-precision. Frequently, initial training sessions are indicated by slowed overall performance to boost movement precision. As learning progresses, performance speed is higher once precision needs are also met. The therapist must record the proper time it

requires to complete the task by having several errors together. Reduced focus and effort are indicative of enhanced performance and need to be documented. A high level of cognitive monitoring is vital for very early learning (cognitive stage).

In comparison, performance across the autonomous and associated phases of motor learning is recognised by a reducing of monitoring and a rising of automaticity. As learning progresses, performance is frequently characterised by consistency. As a result, the variability of the obtained skills across training sessions is anticipated to decrease. Performance observations should only be considered to indicate initial learning since they may not be correct for long-term learning. For example, performance can be temporarily increased with intensive training but not retain for long-term or conversely, other factors like tiredness, monotony, poor motivation, anxiety, or perhaps medications can bring performance to decline (e.g., a fatigued and stressed patient with Multiple sclerosis (MS) may perform badly during scheduled treatment but comes back later after rested may perform smoothly) while learning may remain occurring.

After a period of constant improvement, the performance is expected to level off, and this is called performance plateaus. During plateaus, learning might remain going on, whereas performance is not changing. Problems also occur together with the measurement instruments selected. Failure to show improved overall performance is often the result of ceiling effects, defined as the highest level of performance where more improvement cannot be detected due to restrictions in the performance measure while floor effects are the lowest detectable level of performance (Schmidt & Lee, 2011).

2.2.3.2 Retention Tests

Retention tests are more reliable to determine learning outcomes. Retention refers to the ability regarding the learner to show the skill over time and after a period without any practice (retention interval). A retention test is defined as "a performance test administered after a retention interval for the purposes of assessing learning." (Schmidt & Lee,

2011). It provides a crucial measure of learning. Retention intervals may be of different lengths. For instance, a patient who is seen only once per week in an outpatient hospital is asked to show a skill practiced from the prior week. Performance after the retention interval is that when compared with performance on the original training session, a slight decline in performance may occur but should come back to original performance after a few training sessions (termed warmup decrement). Any verbal cueing or knowledge understanding of outcomes (KR) should not be provided during the retention trial. This very same patient might be given a home workout program (HEP), which includes the daily exercise of the preferred skill. If on the go back to the health care institution several days later, the overall performance of the desired skill has not been maintained or perhaps has deteriorated, the psychologist may reasonably conclude the patient has not been thorough with the HEP as well as learning has not been retained (Schmidt & Lee, 2011).

2.2.3.3 Transfer Tests

Transfer of learning describes the gain (or maybe loss) in the capacity for task performance in a single task as being an outcome of training on some other task. Learning obtained through the criterion task improves (positive transfer) or possibly detracts from (negative transfer) learning on various other tasks. For instance, the patient with stroke practices feeding skills performed by the less affected UE. More affected UE is also examined after that. The therapist needs to observe and record the effectiveness of the last practice (e.g., frequency and number of training trials, time, effort) on functionality working with the more affected extremity. Transfer of learning is better when activities have similar responses and stimuli.

2.2.3.4 Adaptability

Adaptation is defined as the ability to modify and adapt to how movements are carried out in reaction to changing environmental demands and tasks. Therefore, the individual can apply a learnt skill to the learning of some other similar activities. For instance, people who learn to transmit from the wheelchair-to-platform mat can implement that learning how to various other variants of transfers (e.g., wheelchair-to-bathtub or wheelchair-to-

car). The number of training sessions, time, and effort needed to do these new kinds of transfers should be noticed and recorded. These variables are usually reduced from that necessary to acquire the initial skill.

2.2.3.5 Resistance to Contextual Change

Resistance to contextual change is a crucial measure of learning. This is the adaptability required to do a motor task in altered environmental circumstances. Usually, an individual that has obtained a skill (e.g., walking with a cane) must have the ability to apply that learning to variable and new environments (e.g., walking at home, walking outdoors, walking downtown on a crowded street). The therapist observes as well as records how well someone is in executing the skill in the new and different environments. The individual who is in a position to do the skill in one environment type, for instance, the individual with TBI who is just able to run within a tightly controlled, clinic setting (closed setting), shows limited as well as mainly non-functional skills in some other locations. This patient is not very likely to go back home independent within the community setting (open setting), as well as will probably need placement within an assisted living (structured) setting.

2.2.3.6 Active Problem Solving

The patient who can participate in active introspection and self-evaluation of performance, as well as reach decisions independently about the best way to enhance performance, demonstrates a crucial component of learning. Some physical therapists overemphasise instructed movements as well as error-free training. Even though this could be essential for safety reasons, insufficient exposure to performance errors might prevent the patient from developing capabilities for self-evaluation. In an era of fiscal limitations and responsibility on the quantity of actual physical therapy sessions allowed, most patients are only able to do just the simple skills while in active rehabilitation. Much of the required learning of functional skills takes place after discharge and during outpatient sessions. It is impossible for the therapist to create training sessions to satisfy all the challenges a patient is facing. The final objective of rehabilitation is the independence in function, and it can be fulfilled through the acquisition of independent problem

solving/decision-making skills. The therapist has to encourage, observe, and record this crucial function.

2.2.4 Types of Motor skills and learning

2.2.4.1 Types of skills

Motor development is the evolution of changes in motor behaviour happening as an outcome of development, maturation, and experience (Schmidt & Lee, 2011). Foundational abilities are discovered in childhood and infancy with the emergence of specific markers of developmental maturation (Bayley, 1935; Gesell, 1940; McGraw, 1945). These skills are known as developmental motor skills, although they are best considered functional motor skills since they stay a permanent part of motion experience throughout life. Examples include movements like rolling over and getting up out of bed. Motor skills could be categorized based on specific characteristics or attributes into four main groups:

- Transitional mobility describes abilities that enable action from one posture to the next (e.g., sit-to-stand, supine-to-sit).
- Static postural control (stability) describes the capability to keep a body posture with the orientation of the centre of mass (COM) across the base of support (BOS), and the body held steady (e.g., holding in resting, kneeling, or perhaps standing).
- Dynamic postural command (controlled mobility) is the potential to keep postural stability while areas of the body are in action. Examples include weight-maintaining or shifting a posture with the inclusion of progressively more complicated moves (e.g., sitting with top trunk rotation and upper extremity (UE) standing or reaching with lesser extremity (LE) stepping).
- Skill may be the highest degree of motor behaviour and has highly coordinated movement patterns, including grasp and locomotion and manipulation.

2.2.4.2 *Types of learning*

There is evidence supporting that during motor learning phases, there are representational changes in different cerebral areas over the process of acquiring new skills (Fig. 2.7). This model of cerebral plasticity, presented by Doyon et al. (2005), suggests that those changes are different depending on the stage of learning and the type of learning (Motor sequence learning or Motor adaptation). There are five distinct phases in this model:

1. Fast learning: comparable to cognitive processes (early).

2. Slow learning: skill acquired through several practice sessions (later).

3. Consolidation: happens in the interval between practice sessions. Consolidation of a motor sequence occurs in the striatum, while the Consolidation of a motor adaptation occurs in the cerebellum.

4. Automatization: motor skill is learnt, and acceptable performance is achieved. Depending on the type of learned skill, the distribution of the skill in the cerebral network is different (either involves the cortico-cerebellar or the cortico-striatal circuit). To be more specific, for motor adaption, there is an increased activity related to the representation of this skill in the cerebellum, parietal cortex, and its associated cortical regions while the striatum is no longer necessary. For motor sequence learning, the pattern of plasticity is completely reversed; the cerebellum is no longer required while the representational changes occur in the striatum, motor-related cortical regions, parietal, and structures.

5. Retention: even after a long period without any practice, a well-learned motor skill can be recalled again; this is because the same cortico-subcortical systems are reactivated. The pattern is very similar to the previous phase, for motor adaption, the retention of the skill is maintained in the cortico-cerebellar system, while for the motor sequence learning, it is maintained in the cortico-striatal circuit.
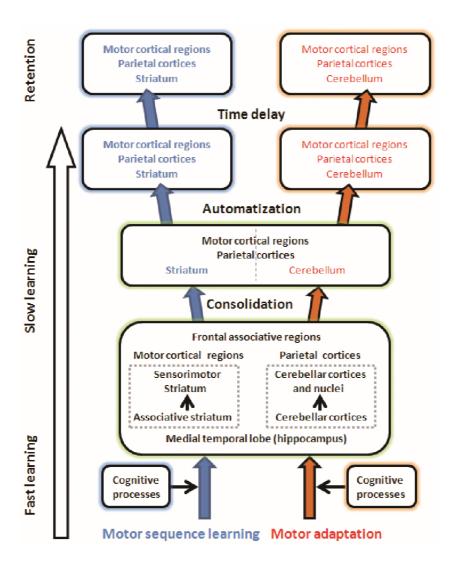
Figure 2.7: A model of Doyon and colleagues describing the cortico-striatal and cortico-cerebellar circuits for motor learning. Blue parts are for motor sequence learning, and red parts are for motor adaptation. Brain regions involved in both types are black (adapted from Doyon & Benali, 2005).

As mentioned in this section, motor behaviour is very crucial for motor development and motor skill is just a highest degree of motor behaviour. The next section will present different interactive motor behaviours where two or more people interacting to each other, this kind of behaviour involve all four main groups of motor skills as mentioned above.

2.3   Interactive motor behaviours

2.3.1 Introduction

Many real-life tasks involve motor interaction between two or more people, e.g. dancing, competing in sport, lifting an object, etc. Such tasks require participants to make decisions and have their strategies to accomplish. One important aspect of rehabilitation techniques based on motor learning theories is that the quality of the learning session relies on the sequence selection of actions (in the task with multiple options) of the performer to finish the task (Huang & Krakauer, 2009). Thus, the understanding of how humans interact (collaborate, compete, cooperate) to each other (behaviours) is critical to both motor learning and rehabilitation. The cost function has been widely used by researchers to determine the motor behaviours in humans (Burdet et al., 2010; Yang et al., 2011; O'Sullivan et al., 2009). To be more specific, the function is used to evaluate optional motor interactions to accomplish the task based on the concurrent minimisation of error (e) and effort (u), which can be modelled as:

$$V(t) \equiv \alpha e^2(t) + \beta u^2(t), \alpha, \beta > 0 \qquad (1)$$

2.3.2 Divisible/interactive   tasks   and   agonistic/ antagonistic tasks

According to Game Theory (Myerson, 1991), interactive tasks (or games) are tasks in which one participant/ player's decision influences the other participant/ player. A Nash equilibrium is a state in which each player is assumed to know the equilibrium strategies of the other players and nothing to gain by any player to change only his/ her strategy unilaterally. Jarrasse´, Charalambous & Burdet (2012) developed a framework to describe and implement joint motor behaviours between two participants executing tasks. There are two antagonisms of a task: divisible/interactive, and agonistic/antagonistic. Divisible tasks consist of independent subtasks performed by each agent. The task can be either performed by each agent alone, like painting a wall together (Bratman, 1992), or perhaps the task in the left panel of Fig. 2.8, in which two animals can pull a rope to control a

pallet and get food. Another example of divisible tasks such as a hybrid force-position controller where position and force controls are independently performed in different subspaces, this kind of task has disjunct but supportive subtasks (Raibert & Craig, 1981). It is not necessary for the two agents to have information regarding the other agent to be successful in their particular subtask in the divisible tasks. As the two agents are acting separately, each agent can reduce their error and effort to the minimum. The interactive task is when one agent needs a partner (at minimum) to undertake the task or subtasks. The interactive task is defined in the Game Theory as tasks in which the activity of one agent impacts the other. The centre panel of Fig. 2.8 illustrates an interactive job that has long been employed to look at the social behaviour of animals like chimpanzees (Crawford, 1937), elephants (Drea & Carter, 2009) and hyenas (Plotnik et al., 2011). In this particular task, an animal cannot be successful in getting the food without the assistance of its partner. The behaviour of the agents is much more complicated in the interactive tasks when comparing to a divisible task since the agents' actions are dependent. As a result, the cost function in this task is also dependent on both agents.

Antagonistic or agonistic can be applied for both interactive and divisible tasks. In an antagonistic task, there is a conflict of interest from the agents: the performance enhancement from one agent can affect negatively the other (fig 2.8 – right panel). The gain or loss of an agent in terms of utility is balanced by the loss or gain of the other agent. If the entire gains of the agents are included up, and the overall losses are subtracted, they are going to sum to zero; this kind of task is considered as a competitive task (e.g., arm wrestling, rope pulling, and fighting games) and also refer to zero-sum games in game theory (the entire advantage to each player in the game, for each blend of strategies, always contributes to zero). Generally, there is no common task, only distinct subtasks performed by each agent. On the contrary, in agonistic tasks, there is a common task; thus, the improvement of such a task can be contributed by the performance enhancement of each agent in subtask. Lots of interactive tasks like moving a huge table together,

mating, or dancing, in which joint action is the key to be successful, can be fit into this category. Middle and left panels of Fig. 2.8 describe agonist tasks in which the cooperative behaviour of interactive tasks match to the cooperative games of game theory.

Divisible tasks with a co-active behaviour can be different depending on the task: in an agonistic task like illustrated in the left panel of Fig. 2.8, co-active behaviour will aid both agents while in an antagonist task as shown in the right panel of Fig. 2.8, it will be detrimental. Likewise, interactive tasks could be either agonistic, such in the centre panel of Fig. 2.8, or perhaps antagonistic, when a Sumo fighter pushes as much as he can against the opposition and suddenly drops the force to destabilize him.
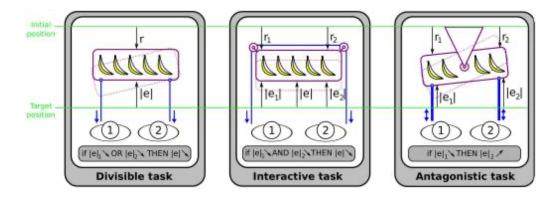
Figure 2.8: Example of various kinds of tasks two agents can execute. Simple tasks in which two animals can pull a rope so that they can approach a pallet with food. e_i is a measure of error relative to the target while r_i is an increasing reward when approaching the target. Each agent plays a part in its own subtask (i.e., pulling the rope), which helps to have the pallet for both animals in the divisible task. The two agents need certainly to collaborate in order to finish the job successfully in the interactive task. The performance of one agent is detrimental to the other in the antagonistic task. (Adapted from Jarrasse′, Charalambous & Burdet, 2012)

2.3.3 Types of interactive task

Assuming there are two agents, agent 1 and agent 2, interact to each other in an interactive task, they may want to:

Collaborate: In collaboration, participants try to have a consensual strategy to solve the problem. There are no pre-allocated roles, but spontaneous roles formed from the agreement between agents based on their discussions during the task. This kind of behaviour is also known as symmetric behaviour, i.e. the structure of the cost function does not change under permutation from 1 to 2. Assuming one agent can estimate their partner's error ($\hat{e}$) and effort ($\hat{u}$)

$$V_i(t) \equiv \alpha_i e_i^2(t) + \beta_i u_i^2(t) + \left(\gamma_i \hat{e}_j^2(t) + \delta_i \hat{u}_j^2(t) \right), \quad i \neq j, \; i,j = 1,2 \qquad (2)$$

Cooperate: Both agents have the same goal and need to work with each other to finish the task. However, unlike the collaboration, in cooperation, there are different roles for agents before the beginning of the task, and those roles remain unchanged until the task accomplished. Those roles are not equal; therefore, cooperation is known as an asymmetric behaviour, i.e. there is an asymmetry in the cost functions under permutation from 1 to 2. Relationships of a cooperative behaviour could be master-slave and teacher-student.

In a master-slave relationship, the master only cares about himself while the slave has to fulfil the master's demands

$$V_1(t) \equiv \gamma_1 \hat{e}_2^2(t) + \delta_1 \hat{u}_2^2(t) \quad \text{Slave} \qquad V_2(t) \equiv \alpha_2 e_2^2(t) + \beta_2 u_2^2(t) \; \text{Master} \quad (3)$$

In a teacher-student relationship, the teacher assists the student to do his task and improve his capabilities. A good teacher would minimize his effort to challenge the student, thus giving him a chance to build up his capabilities.

$$V_1(t) \equiv \gamma_1 \hat{e}_2^2(t) + \beta_1 u_1^2(t) \; \text{Teacher} \quad V_2(t) \equiv \alpha_2 e_2^2(t) + \beta_2 u_2^2(t) \; \text{Student} \quad (4)$$

Compete: In completion, agents may have different goals thus they have to focus on their effort and error and impede the competitor's performance if possible

$$V_i(t) \equiv \alpha_i e_i^2(t) + \beta_i u_i^2(t) - \left(\gamma_i \hat{e}_j^2(t) + \delta_i \hat{u}_j^2(t) \right), \, i \neq j, \, i,j = 1,2 \qquad (5)$$

2.4 Chapter summary

This chapter reviews background to motor control and motor learning aiming to provide an understanding of how voluntary movements are planned in the human brain, motor skills are learnt, how many stages of motor learning and the different types of interactive motor behaviours when two or more people interacting to each other.

The principles and terminology regarding motor learning and interactive motor behaviours from this chapter are used throughout this thesis: Chapter 3 (section 3.3) explains the knowledge of motor learning (learning stages and measures of motor learning performance) can help to form strategies to improve motor function while studies in chapter 6 and 7 were designed based on the interactive motor behaviours (collaborative tasks) introduced in this chapter. The cost function presented in this chapter was also applied in chapter 7 to measure the participants' performance.

Chapter 3: Physical Rehabilitation Methods

Physical rehabilitation or simply called rehab is a type of treatment that helps people with disability due to brain, bones, muscles or nerves injury to regain their body functions. Chapter 2 introduced theories of motor learning in human in general. Chapter 3 presents how motor learning being integrated into strategies to improve motor function for patients who require physical rehabilitation.

This chapter introduces the classification of functioning, disability and health, the process of patient management, how therapists should communicate and coordinate with other professionals and/or giving instruction to patients, procedural interventions, and practice strategies for patients with motor disfunction. The background knowledge presented in this chapter is essential to design the functionality of the proposed framework in chapter 5.

3.1 Classification of functioning, disability, and health

The World Health Organisation (WHO) provides a framework to categorise health conditions. The framework called *International Classification of Functioning, Disability, and Health (ICF)* - also endorsed by other international organisations such as the American Physical Therapy Association (APT), the World Confederation for Physical Therapy (WCPT), the America Therapeutic Recreation Association (ATRA) - defines health condition, impairment, activity limitation, and participation restriction (WHO, 2019). Figure 3.1 illustrates the ICF model of disability.
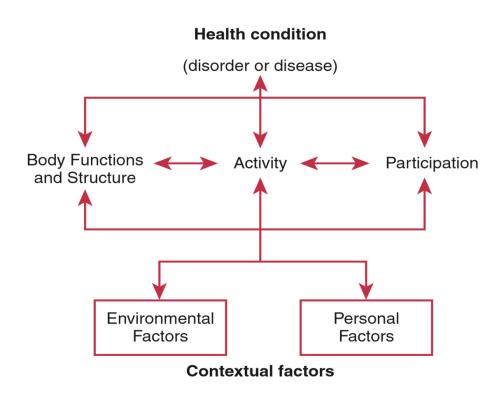
Figure 3.1: ICF Model of Disability. The WHO classification of functioning, disability, and health (ICF). (Adapted from World Health Organization, 2002)

Impairments refer to the problems that occur in body function (specifically physiological function) or structure (anatomical parts) of an individual. The resultant significant loss or deviation is the immediate consequence of a disease, injury, disorder, trauma or other health conditions like stress, aging, congenital abnormality or genetic inclination. For example, a patient with stroke may present with sensory loss, paresis, dyspraxia, and hemianopsia (direct impairments) (O'Sullivan et al., 2014).

Impairments can be mild, medium, extreme or complete and might be constant or settling as recovery developments. Impairments may likewise be backhanded (optional), the sequelae or difficulties that begin from different frameworks. They can result from pre-existent impairments or the dysfunction of a growing multisystem that happens with continued bed rest and idleness, an ineffective plan of care (POC), or lack of rehabilitation intervention. Examples of indirect impairments include decreased vital capacity and endurance, disuse atrophy and weakness, contractures, decubitus ulcers, deep venous thrombosis, renal calculi, urinary tract infections, pneumonia, and depression. The name composite impairments allude to impairments that are the outcome of various fundamental sources, the linked impacts of both indirect and direct impairment (such as balance deficiencies, stride shortages). Movement restrictions are complications an individual may have in executing actions or tasks. Movement restrictions can include constraints for the performance of psychological and learning aptitudes, relational abilities, functional mobility skills (FMS) (such as transfers, walking, lifting or carrying objects), and daily life activities (DLA). Fundamental daily life activities (FDLA) include self-care exercises of hygiene, toileting, bathing, drinking, eating, dressing, and social (interpersonal) communications. The person with stroke may demonstrate difficulties in all of the above areas and be unable to execute the activities, errands, and exercises that constitute the "standard exercises" for this person. Cooperation limitations are issues that an individual may encounter with inclusion in life circumstances and cultural collaborations. Classes of life roles incorporate home administration, (work/play/school), and leisure/community. These include instrumental daily life activities (IDLA)

such as housecleaning, telephoning, preparing meals, shopping, and managing finances, as well as work and leisure activities (e.g., sports, recreation, trips). Thus, the individual with stroke is unable to resume societal roles such as working, parenting, attending church, or traveling. Execution qualifiers demonstrate the level of participation limitation (trouble) in executing actions or tasks in a person's current genuine condition. All traits of the social, physical, and attitudinal world majorly contribute to creating the environment. The range of difficulty can be from mild to medium to extreme to complete. Limit qualifiers signify the level of activity constraint and are utilized to depict a person's most elevated degree of working (ability to do the task or action). Qualifiers can range from the assistance of a device (e.g., adaptive equipment) or another person (minimal to moderate to maximal assistance) or environmental modification (home, workplace). Thus, the patient with stroke may demonstrate moderate difficulty in locomotion in the home surroundings (performance qualifiers) and require the usage of an ankle-foot orthosis, small-based quad cane, and moderate assistance of one (capacity qualifiers). Natural factors make up the social, physical, and attitudinal atmosphere in which individuals live and work. Elements range from goods or products and innovation (for individual daily routine use, mobility and transportation, communication) and physical factors (home environment, terrain, climate) to social support and relationships (friends, family, providers of personal care), attitudes (individual and societal), and institutions and laws (housing, communication, transportation, legal, financial services, and policies). Qualifiers include factors that serve as barriers (disablement risk factors) or facilitators (assets). The range of barriers can be from mild to medium to extreme to complete. Facilitators can also range from mild to medium to significant to complete (O'Sullivan et al., 2014).

3.2 Client/Patient management

Steps in client or patient management include (1) patient's examination; (2) Data evaluation and problems identification; (3) determining the physical

therapy diagnosis; (4) POC and prognosis determination; (5) implementation of the POC; and (6) Patient's re-examination and treatment results evaluation (Figure 3.2).

DIAGNOSIS
Both the process and the end result of evaluating examination data, which the physical therapist organizes into defined clusters, syndromes, or categories to help determine the prognosis (including the plan of care) and the most appropriate intervention strategies.

EVALUATION
A dynamic process in which the physical therapist makes clinical judgments based on data gathered during the examination. This process also may identify possible problems that require consultation with or referral to another provider.

PROGNOSIS
(Including Plan of Care)
Determination of the level of optimal improvement that may be attained through intervention and the amount of time required to reach that level. The plan of care specifies the interventions to be used and their timing and frequency.

EXAMINATION
The process of obtaining a history, performing a systems review, and selecting and administering tests and measures to gather data about the patient/client. The initial examination is a comprehensive screening and specific testing process that leads to a diagnostic classification. The examination process also may identify possible problems that require consultation with or referral to another provider.

OUTCOMES
Results of patient/client management, which include the impact of physical therapy interventions in the following domains: pathology/pathophysiology (disease, disorder, or condition); impairments, functional limitations, and disabilities; risk reduction/prevention; health, wellness, and fitness; societal resources; and patient/client satisfaction.

INTERVENTION
Purposeful and skilled interaction of the physical therapist with the patient/client and, if appropriate, with other individuals involved in care of the patient/client, using various physical therapy methods and techniques to produce changes in the condition that are consistent with the diagnosis and prognosis. The physical therapist conducts a reexamination to determine changes in patient/client status and to modify or redirect intervention. The decision to reexamine may be based on new clinical findings or on lack of patient/client progress. The process of reexamination also may identify the need for consultation with or referral to another provider.

Figure 3.2: Components of patient management leading to the finest results. (APTA Guide to Physical Therapist Practice 4, p. 35)

3.2.1 Examination

The examination includes recognising and defining the issues of patients along with the resources accessible to determine the suitable interference. It comprises three segments: an understanding history of patients, a review of the system, and tests and methodologies. The examination starts with the initial entry or patient recommendation and proceeds as a continuous procedure in the course of care. Continuous re-examination enables the therapist to measure progress and adjust interventions as suitable.

3.2.2 Evaluation

Information collected from the initial examination should then be sorted out and investigated. The specialist identifies and organizes the patient's impairments, movement confinements, participation limitations and creates a list of problems. It is critical to precisely perceive those clinical

issues related to the primary condition and those related to co-morbid situations.

Impairments, activity limitations, and participation restrictions must be analysed to identify causal relationships. For example, shoulder pain in the patient with hemiplegia may be due to several factors, including hypotonicity and loss of voluntary movement, which are direct impairments, or soft tissue damage/trauma from improper transfers, which is an indirect impairment, resulting from an activity. Determining the causative factors is a difficult yet critical step in determining appropriate treatment interventions and resolving the patient's pain. The skilled clinician is able to identify the role barriers and facilitators in the patient's environment in order to incorporate measures to minimize or maximize these factors into the POC. A POC that emphasizes and reinforces facilitators enhances function and the patient's ability to experience success. Improved motivation and engagement are the natural outcomes of reinforcement of facilitators. For example, the patient with stroke may have intact communication skills, cognitive skills, and good function of the uninvolved extremities. Facilitators can also include supportive and knowledgeable family members/caregivers and an appropriate living environment.

3.2.3 Diagnosis

A medical diagnosis refers to the identification of a disorder, disease or condition (pathophysiology/pathology) by estimating the presenting marks, indications, side effects, history, laboratory test outcomes, and systems. It is fundamentally identified at the cellular level. The term of diagnosis utilized by the physical therapist to "recognize the effect of a condition on work at the system level (particularly the development framework) and at the level of the entire individual (Fagan, 1975). Thus, the term is used to clarify the professional body of knowledge and the physical therapist's role in health care. For example, Medical diagnosis: Cerebrovascular accident (CVA) Diagnosis of Physical Therapy: Impaired motor operations and sensory

reliability related to non-progressive issues of the central sensory frameworks—gained in pre-adulthood or maturity (Fagan, 1975). Medical diagnosis: Spinal cord injury (SCI) Physical therapy diagnosis: Impaired motor function, peripheral nerve integrity, and sensory integrity associated with nonprogressive disorders of the spinal cord (Fagan, 1975). The diagnosis procedure incorporates coordinating and examining the information acquired during the evaluation to define the condition of client or patient in terms that will direct the prognosis and determination of intervention methodologies during the POC improvement. The Guide to Physical Therapist Practice organizes diagnostic categories specific to physical therapy by preferred practice patterns (Fagan, 1975). There are four main classifications of conditions: Neuromuscular, Musculoskeletal, Integumentary, and Pulmonary/Cardiovascular, with preferred practice patterns identified in each. The patterns are described fully according to the five features of client/patient management (such as examination, evaluation, diagnosis, prognosis, and intervention). Each pattern also includes re-examination to evaluate progress, universal results and standards for physical therapy amenities termination. Exclusion and Inclusion standards for each practice pattern and criteria for multiple pattern classification are also presented. The patterns represent the collaborative effort of experienced physical therapists who detailed the broad categories of problems usually viewed by physical therapists within the scope of their knowledge, experience, and expertise. Expert consensus was thus used to develop and define the diagnostic categories and preferred practice patterns. Given the central role of physical therapists as movement specialists, the therapist will need to focus the diagnosis on the results of activity analysis and movement problems identified during the examination when formulating the prognosis and POC. The use of diagnostic categories specific to physical therapy, as Sarhman points out, (1) allows for successful communication with colleagues and patients/caregivers about the conditions that require the physical therapist's expertise, (2) provides an appropriate classification for establishing standards of examination and treatment, and (3) directs examination of treatment effectiveness, thereby

enhancing evidence-based practice (Childs & Cleland, 2006). Physical therapy diagnostic categories also facilitate successful reimbursement when linked to functional outcomes and enhance direct access to physical therapy services.

3.2.4 Prognosis

The term prognosis refers to "the predicted optimal improvement level in function and the time required to reach that level" (Fagan, 1975). An exact prognosis can be settled at the start of treatment for particular patients. For other patients with more complicated conditions such as severe TBI accompanied by extensive disability and multisystem involvement, prognosis or prediction of level of improvement can be determined only at various increments during the course of rehabilitation. Information on recovery designs (disorder stage) is sometimes valuable to take decisions. The measure of time required to reach ideal recovery is a significant assurance, one that is required by Medicare and many other insurance providers. Predicting optimal levels of recovery and time frames can be a challenging process for the novice therapist. Use of experienced, expert staff as resources and mentors can facilitate this step in the process of decision making. For each preferred practice pattern, the Handbook to Physical Therapist Functions includes a wide range of estimated number of appointments per episode of care (Fagan, 1975).

3.2.5 Plan of Care

The POC summaries projected patient management. The therapist evaluates and integrates data obtained from the history of client or patient, the systems analysis, and tests and methodologies within the context of other factors, including the patient's general health, living atmosphere, accessibility of social supportive networks, and potential discharge destination. Multisystem involvement, severe impairment, and functional loss, extended time of involvement (chronicity), multiple co-morbid conditions, and medical stability of the patient are important parameters that increase the complexity of the decision-making process.

A significant focal point of the POC is delivering important changes at the social/individual level by diminishing activity restrictions and participation confinements. Accomplishing freedom in movement or DLA, work routine, or involvement in recreational exercises is important to the patient/client in terms of improving quality of life (QOL) (Glynn & Weisbach, 2011). QOL is defined as the sense of total well-being that encompasses both physical and psychosocial aspects of the patient/client's life. Finally, not all impairments can be remediated by physical therapy. Some impairments are permanent or progressive, the direct result of unrelenting pathology such as amyotrophic lateral sclerosis (ALS). In this example, a primary emphasis on reducing the number and severity of indirect impairments and activity limitations is appropriate. Essential components of the POC include (1) projected objectives and estimated results; (2) the predicted level of ideal development; (3) the specific utilization of interventions, including type, frequency, and duration; and (4) criteria for discharge.

3.2.6 Interventions

The intervention, which is defined as the purposeful collaboration of the physical therapist with the client or patient and, when suitable, different people engaged in the care of clients or patients, utilizing different physical therapy techniques and procedures to modify conditions. Components of physical therapy intervention incorporate communication, coordination, and documentation; client or patient-related instruction; and procedural interventions (Figure 3.3).

The Three Components of Physical Therapy Intervention

Coordination, Communication, Documentation	Patient/ Client-Related Instruction	Procedural Interventions

Therapeutic exercise

Functional training in self-care and home management, including activities of daily living (ADL) and instrumental activities of daily living (IADL)

Functional training in work (job/school/play), community, and leisure integration or reintegration, including IADL, work hardening, and work conditioning

Manual therapy techniques, including mobilization/manipulation

Prescription, application, and, as appropriate, fabrication of devices and equipment (assistive, adaptive, orthotic, protective, supportive, or prosthetic)

Airway clearance techniques

Integumentary repair and protective techniques

Electrotherapeutic modalities

Physical agents and mechanical modalities

Figure 3.3: The three components of physical therapy intervention. (APTA Handbook to Physical Therapist Functions 4, p. 98)

Coordination and Communication

Therapists need to be able to effectively communicate with all professionals of the rehabilitation team, either directly (e.g. conferences, team meetings) or indirectly (e.g. documentation in the medical record).

As a result, effective communication will improve collaboration and understanding. Therapists also has coordinating responsibility at many different levels. For example, the therapist delegates appropriate aspects of

treatment to physical therapy assistants and oversee the responsibilities of physical therapy aides. The therapist coordinates care with other professionals, family, or caregivers regarding a specific treatment approach or intervention. For example, for early transfer training to be effective, consistency in how everyone transfers the patient is important. The therapist also coordinates discharge planning with the patient and family and other interested persons. Therapists may be involved in providing POC recommendations to other facilities such as restorative nursing facilities.

Patient-related instruction is significant to make certain of optimal care and effective recovery. Communication strategies are developed within the context of the patient/client's age, ethnic backgrounds, linguistic skills, level of education, and the presence of specific communication or cognition impairments. Therapists may provide direct one-on-one instruction to a variety of individuals, including patients, clients, families, caregivers, and other interested persons. Additional strategies can include group discussions or classes, or instruction through printed or audio-visual materials. Educational interventions are focussed toward understanding and ensuring the condition of the patient, training in specific exercises and activities, determining the significance of interventions to enhance function, and achieving an anticipated course. In addition, educational interventions are directed toward ensuring a successful transition to the home environment (instruction in-home exercise programs (HEP)), returning to work (ergonomic instruction), or resuming social activities in the community (environmental access). It is important to document what was taught, who participated, when the instruction occurred, and overall effectiveness. The need for repetition and reinforcement of educational content should also be documented in the medical record.

Procedural interventions

Physical therapy with highly skill involves extensive procedural interventions diversity, which can be comprehensively classified into three primary categories: restorative interventions, compensatory interventions, and preventative interventions.

Restorative interventions are focused on improving or remediating the status of a patient in terms of impairments, participation confinements, activity restrictions, and functional recovery. The involved segments are targeted for intervention. This approach assumes an existing potential for change (e.g., neuroplasticity of brain and spinal cord function; potential for muscle strengthening or improving aerobic endurance). For example, the patient with imperfect SCI undergoes locomotor exercise using the support of body weights and a treadmill training (BWSTT). Patients with chronic progressive pathology (e.g., the patient with Parkinson's disease) may not respond to restorative interventions aimed at resolving direct impairments; interventions aimed at restoring or optimizing function and modifying indirect impairments can, however, have a positive outcome.

Compensatory interventions are concentrated towards supporting optimum function by means of residual abilities. The activity (task) is adapted (changed) in order to achieve function. The uninvolved or less involved segments are targeted for intervention. For example, the patient with left hemiplegia be trained to dress by means of the right UE; the patient with complete T1 paraplegia learns to roll using UEs and momentum. Environmental adaptations are also used to facilitate relearning of functional skills and optimal performance. For example, the patient with TBI is able to dress by selecting clothing from color-coded drawers. Compensatory interventions can be used in conjunction with restorative interventions to maximize function or when restorative interventions are unrealistic or unsuccessful.

Preventative interventions are directed toward minimizing potential problems (e.g., anticipated indirect impairments, participation

confinements, and activity restrictions) and maintaining health. For example, early resumption of upright standing using a tilt table minimizes the risk of pneumonia, bone loss, and renal calculi in the patient with SCI. A successful educational program for frequent skin inspection can prevent the development of pressure ulcers in that same patient with SCI. Interventions are chosen based on the medical diagnosis, the evaluation of examination, the physical therapy diagnosis, the prognosis, and the projected objectives and estimated results. The therapist relies on knowledge of foundational science and interventions (e.g., principles of motor learning, motor control, muscle performance, task-specific training, and cardiovascular conditioning) in order to determine those interventions that are likely to achieve successful outcomes. It is important to identify all possible interventions early in the process, to carefully weigh those alternatives, and then to decide on the interventions that have the best probability of success. Narrowly adhering to one treatment approach reduces the available options and may limit or preclude successful outcomes. The use of a protocol (e.g., predetermined exercises for the patient with hip fracture) standardizes some aspects of care but may not meet the individual needs of the patient. Protocols can foster separation of examination/evaluation findings from the selection of treatments. Watts suggests that clinical judgment is clearly an elegant mixture of art and science (Riddle & Wells, 2004). Professional consultation with expert clinicians and mentors is an effective means of helping the novice sort through the complex issues involved in decision making, especially when complicating factors intervene. For example, a consultation would be beneficial for the inexperienced therapist who is treating a patient that is chronically ill, has multiple co-morbidities or complications, impaired cognition, inadequate social supports, and severe activity limitations. A general outline of the POC is constructed. Schema can be used to present a framework for approaching a specific aspect of treatment and assist the therapist in organizing essential intervention elements of the plan. The therapist should ideally choose interventions that accomplish more than one goal and are linked to the expected outcomes. The interventions should be effectively sequenced to address key

impairments first and to achieve optimum motivational effect, interspacing the more difficult or uncomfortable procedures with easier ones. The therapist should include tasks that ensure success during the treatment session and, whenever possible, should end each session on a positive note. This helps the patient retain a positive feeling of success and look forward to the next treatment.

3.3 Strategies to Improve Motor Function

Neurorehabilitation interventions have evolved over time for the management of patients with disorders of motor function. Many treatment ideas emerged from empirical knowledge and clinical practice. The theory was applied to explain the success of these interventions and to organize them into a coherent treatment philosophy. The understanding of the motor function and its theoretical base has changed over the years. Emphasis on evidence-based practice has resulted in increased validation of therapeutic interventions through research. The therapist's role is to accurately determine the patient's strengths and limitations and to develop a collaborative POC that includes goals and outcomes that match the patient's unique needs. The therapist must also determine an appropriate level of intensity, frequency, and duration of treatment. An important framework for practice is based on the current understanding that movement arises from the interaction of three basic elements: the task, the individual, and the environment (Shumway-Cook & Wollacott, 2012). All three components must be considered in developing a successful POC.

3.3.1 Strategy Development

The general objective during the early cognitive phase of learning is to aid task understanding and establish the early practice. The learner's understanding of the skill and any prevailing or current problems must be determined. The therapist needs to accentuate the importance of the skill in a practically applicable environment. The task needs to appear as essential, necessary and one which can be realistically mastered. The therapist must display the task in the exact manner it is supposed to be done (i.e. harmonized activity with efficient timing and the right performance speed).

This assists the learner to build an inner cognitive map or standard for perfection. Special focus should be given to the desired results and important task components. The therapist needs to highlight the similar features or the semblances to other learned tasks so that plans which are components of other motor programs can be extracted from memory. Components of the environment that are important to smooth performance must be emphasized. Extremely skilful individuals who have successfully undergone rehabilitation can become expert role- models. Their achievement in making a return to the "real world" will equally have a positive impact on encouraging patients who are just getting started with rehabilitation. For instance, it is a daunting task for a therapist who has complete muscles to perfectly demonstrate suitable transfer skills to someone suffering from C6 complete tetraplegia. A successfully rehabilitated former patients who experienced the same kind of injury can perfectly teach the best ways the skill should be executed.

Modelling has been proven to be a powerful learning method even with unskilful patient models. Under such circumstances, the patient/learner learns from the cognitive processing and problem-solving skills applied employed while observing the unskilful model effort to rectify mistakes and achieved the preferred movement (Lee & Swanson, 1991). Also, demonstrations can either be videotaped or live. Creating a video collection of skilled ex-patients is an effective idea to guarantee easy access to effective models. Guided movement entails physically helping the earner with the task he needs to gain a mastery of. It can have significant positive impacts during the early stage of skill learning. (Winstein et al., 1994; Singer & Pease, 1976; Wulf et al., 1998) The hands of the therapist can suitably replace missing elements, stabilize some parts of the body while restraining undesired movements, minimize errors and direct the patient to the right performance. Likewise, it enables the learner to determine the physical and kinesthetics efforts necessary in the task, that is, to master the senses of movement. The helpful use of hands equally dispels fears and brings in confidence while guaranteeing safety.

Verbal direction, "talking someone through the task," is equally a type of guidance that can be applied to enhance performances. As stated earlier, a better performance does not in any way signifies real learning or internalization of a skill. Without effective trial and error, discovery learning, there will only be temporary changes in performance.

To achieve success in the usage of guided movements, it is critical to reduce guidance and combine practice with lively movements as early and as often as possible. Excessive use of guided movements can lead to an overreliance on the therapist for help, therefore making the therapist become a "support system".

The patient who says that he or she is only able to execute the skill if only "my therapist" assists or "I can only follow my therapist methods" is signifying an overdependence on guided movement. Guidance has the maximum level of effectiveness for slow postural responses (positioning tasks) while it is not so effective for ballistic or rapid tasks. During the early practice, the therapist must provide a response accentuating information vital for movement efficacy. The patient must not be overburdened with unnecessary criticism or wordy commands. It is critical to strengthen the right performance and mediate when movement mistakes become regular or when safety becomes a problem. The therapist must make no effort to rectify the many mistakes that are common to this stage but should give space for learning through trial and error.

Feedback, principally visual feedback, is critical during the initial stage of acquisition. The learner should be guided to closely observe the movements. The early performance of the learner's trials can equally be videotaped for later watching. Prompted or directed viewing of the task enhances learning. During the accompanying and independent stages of learning, the patient keeps improving movement strategies with intense practice. Accidental errors reduce. As regular errors become known, feedback can be provided, and solutions developed. The emphasis is on the improvement of skills and consistency of movements in different environments. This will guarantee a

complete array of movement patterns that are adjustable and complements the dynamic requirements of open environments.

The attention of the patient should now be concentrated on a proprioceptive response, the "sensations of the movement." Hence, the patient is guided to attend to the feelings inherent to the actual movement and to relate those feelings with the motor movements. At this stage, guided movements are counterproductive because they restrict the active practice. At the late learning stage, the application of distracters such as continuing discussion or double task training (e.g. ball skills while standing and walking) can provide vital evidence of an increasing level of independent control. It is essential to remember that a lot of patients going through active rehabilitation do not get to this last phase of learning. For instance, in patients with TBI, performance can attain regular levels with controlled environments, while regular safe performance in open community environments is impracticable.

3.3.2 Feedback

Several works of literature in motor learning have established the vital role of feedback in the promotion of motor learning. Feedback can either be intrinsic (inherent), taking place as a natural product of the movement or extrinsic (improved) integrating provided sensory signals that are not typically obtained in the course of the movement. Visual, proprioceptive, cutaneous and vestibular cues are examples of kinds of intrinsic feedback, while auditory, visual and tactile signals are types of extrinsic feedback (e.g. manual signals, verbal signals, biofeedback devices like the pressure-sensing devices (footpad, force plate), electromyogram (EMG). Throughout the therapy, both extrinsic and intrinsic feedbacks can be influenced to improve motor learning. The application of improve feedback functions as a vital source of and assists the learner to connect relationships between the movement limits and resultant action. Simultaneous feedback is provided during the performance of a task, while terminal feedback is provided when the task performance is concluded. Improved feedback about the type of final result generated in connection to the objective is

called knowledge of results (KR). Improved feedback about the quality or type of movement pattern developed is called termed knowledge of performance (KP) (Schmidt & Lee, 2011). Even though the two are essential, the comparative application of KR and KP can differ, dependent on the skill being acquired and the presence of feedback from inherent sources. (Salmoni et al., 1984; Lee et al., 1990; Bilodeau et al., 1959; Magill, 2001; Winstein, 1996). For instance, tracking tasks are extremely reliant on kinesthetic and intrinsic visual feedback (KP) while KR has little impact on the preciseness of the movements. In some other tasks, (e.g. transfers) KR offers vital information on how to pattern the general movements for the subsequent trials while KP may not be so useful. Performance signals (KP) ought to concentrate on important task elements that result in a successful result. The therapist must take the patient's cognitive and physical resources into consideration and equally considers the difficulty of the tasks to be mastered in deciding the possible type of feedback. The following issues are encapsulated in decisions about feedback:

- What kinds of feedback ought to be used (mode)?
- How much feedback should be employed (intensity)?
- What should feedback be provided (scheduling)?

Decisions regarding the type of feedback entail the choice of which inherent systems to emphasized, what form of improved feedback to apply and how to structure extrinsic feedback to intrinsic feedback. The choice of sensory systems is based on the particular analysis results of sensory veracity. The chosen sensory systems must provide correct and functional information. In case an intrinsic system is damaged and produces inaccurate or inadequate information (e.g. damaged proprioception with diabetic neuropathy), the usage of a substitute sensory systems (vision) must be highlighted. Supplementary improved feedback can be applied to improve learning. Decisions are equally dependent on the level of learning. In the early phase of learning, visual feedback is effortlessly brought to conscious focus and thus essential. Less consciously available sensory details like proprioception need to be stressed during the middle and last phases of

learning. Decisions concerning the intensity and planning of feedback (what time and how much) have to be made. Regular improved feedback (e.g. provided after each trial) speedily directs the learner to enhance performance but delays memory and general learning. On the other hand, different feedback (not provided after each trial) delays the early execution of the skill while enhancing performance on memory tests (Bilodeau & Bilodeau, 1958; Ho & Shea, 1978; Sherwood, 1988; Winstein & Schmidt, 1990; Lavery, 1962). This is highly possible due to the improved level of cognitive processing which follows variable feedback presentation. On the other hand, the therapist who overburdened the patient soon after a task completion with unnecessary improved verbal feedback might hinder effective information processing by the learner (Swinnen et al., 1990; Boyd & Winstein, 2006). The decision-making skills of the patients are limited whereas the verbal skills of the therapist dominate. Winstein (1991) stressed that this might explain why several types of research on the efficiency of therapeutic methods mention nominal carryover and restricted retention of recently learned motor skills. Lastly, the withdrawal of improved feedback should be slowly and thoughtfully harmonized with the patient's attempt to rightly use intrinsic feedback systems.

3.3.3 Practice

The second major influence on motor learning is practice. General principles of practice are (1) increased practice results in increased learning and (2) large and rapid improvements in performance are typically observed initially with smaller improvements noted over time. The therapist's role is to prepare the patient for practice and to ensure that the patient practices the desired movements. The practice of incorrect movement patterns can lead to a negative learning situation (interference) in which "faulty habits and postures" must be unlearned before the correct movements can be mastered. The organization of practice will depend on several factors, including the patient's motivation, attention span, concentration, and endurance, and the type of task. Making the task seem important and attainable improves motivation and commitment to practice. Patients who are involved in goal setting and recognize specific practice

parameters (task purpose, schedule, limits) demonstrate an improved commitment to practice. An additional factor that influences practice is the frequency of allowable therapy sessions, which is often dependent on hospital scheduling and availability of services and payment. Planning for effective use of the out-of-therapy practice is important for all patients but especially so for patients with limited access to physical therapy. For outpatients, practice at home is highly dependent on motivation, family support, and a suitable environment. Therapists must consider the cognitive and physical resources of patients and the complexity of the tasks to be learned in determining the type of practice possible. Clinical decisions about practice include the following issues:

- How should practice periods and rest periods be spaced (distribution of practice)?
- What tasks and task variations should be practiced (variability of practice)?
- How should the tasks be sequenced (practice order)?
- How should the environment be structured (closed vs. open)?
- What tasks should be practiced in a parts-to-whole sequence?

3.4   Chapter summary

This chapter provides background knowledge of physical rehabilitation. It describes ICF framework to categorise health conditions, the patient/client management procedure and strategies to design effective POC. Some aspects introduced in this chapter were considered when designing the functionality of the framework in chapter 5. For example, the framework should be able to support the patient management process from examination to intervention or be able to maintain communication and store patient's data securely. Other aspects regarding how to design practice to improve motor function were also used for experiments in chapter 6 and 7. For instance, the amount and type of feedback (intrinsic feedback such as auditory, visual and tactile feedback for experiments in chapter 6 - section 6.2 and 6.3 or both intrinsic and extrinsic feedback in chapter 7) should be provided to the participants, or not giving too much guidance to avoid an overreliance on the researcher for help (e.g. experiment in chapter 6 - section 6.1).

Chapter 4: Overview of robotic telerehabilitation systems and the effect of network failure

Chapter 4 introduces different types of robotic telerehabilitation systems and category of telerehabilitation applications. This chapter also explains how the network failures can affect a haptic and VR-based telerehabilitation system. It also presents multiple methods to reduce the negative effects of the poor network conditions.

4.1 Introduction & Overview

4.1.1 Physical rehabilitation

The use of certain devices to correct adult motor impairment by controlling the patient movement was employed by Roda et al. (2015). They suggested a system relying on procedures peculiar to Ambient Intelligence where different devices are combined and results in a reaction of multi-agent systems (MAS) according to the context. This allows physiotherapists to modify and deduce from existing therapies designed to meet patient needs.

With the use of third-party sensors, data such as the patient's oxygen level, pose, gesture, mood, basic metabolic panel (BMP), and stress level can be collected. Microsoft Kinect is used to monitor and control all motor tasks executed by the patient during rehabilitation. Collected data can be analysed to determine pain and fatigue instead of just having a vague idea. For instance, with an inference engine, an agent can express how the transition is made using linguistic values rather than numerical values without infringing on privacy requirements. Performing cardiac rehabilitation during the second (sub-acute) and third (intensive outpatient therapy) phase requires a large amount of data to be analysed as fast as possible.

Mesa et al. (2018) suggested a system that offers support in analysing data, grouping events, and visualization. Rehabilitative exercise such as (i) riding the stationary bike at different speeds; (ii) lower body workout; (iii) treadmill exercise at varying speeds and inclinations; and (iv) upper body workout, have involved such a MAS. Dealing with rehabilitation systems heightens the challenge of establishing cooperation with remote participants and the most important factors needed to tackle this challenge are data and awareness of context. Thus, information awareness is essential in ensuring rehabilitation is designed to suit the needs of cognitive and physical rehabilitating users (Teruel et al., 2016).

When dealing with Upper Limb Rehabilitation (ULR), Rodriguez et al. (2015) recommended an agent-based system that provides patients with personalized exercises and, thus, a custom-made ULR. Context-awareness is a basic ingredient of such systems as it facilitates run-time adaptability. The system therefore simultaneously performs three abstract tasks: (i) monitoring and recording patients' movements in exercising the upper limb, (ii) analysing certain data of patient (e.g., BPM, skin conductance), an agent is responsible for determining the stress/fatigue level; (iii) the agent as a "virtual therapist" adjusts ULR's parameters.

A multi-agent system that could identify human movements, postures, and spot harmful activities so it can prevent risk situations was developed by Felisberto et al. (2012). This was done using wireless sensor nodes and energy harvesting technologies to create a wireless body area network (WBAN). Also, Robotic manipulators have been used in agent-based solutions and an intelligent agent constantly examines possible profile variations in order to recognize deterioration in physical and posture that could lead to accidents.

Significant contributions have been made to the relationship between therapist, trainee, and patient. (Adibi, 2015) states that trainee learning stages may be improved by formalizing and enhancing the accuracy and input to be understood. Mutingi et al. (2015) suggested an agent-based decision-making solution for drug delivery. The authors considered bio-physical signals such as blood-pressure, BMP, and respiration. When these parameters are examined alongside drug therapy, it will provide valuable information about patient and pathology evolution to medical staff and facilitate patient requirement comprehension. This will make it easier to gather data and increase resource availability while reducing workload.

4.1.2 Cognitive rehabilitation
The need for Cognitive Rehabilitation may arise in many circumstances. It could arise as a result of Acquired Brain Injury (ABI) also known as the older adult silent epidemic. Such according to Rohling et al. (2009) requires practice such as practical communication, visuospatial, attention, memory,

language and comprehension training. Abreu et al. (2011) suggested a set of 3D games for the rehabilitation of neuropsychiatric disorders, for this to work. There will be an automatic agent-based control managing the software processes while the patient is playing. A multi-agent system was designed by Roda et al. (2017) which (i) supports the execution of the above-mentioned ABI related therapies, and (ii) monitor and assess the performed activities and patient state (e.g., stress level, emotional state, BPM, and oxygen level).

Smith et al. (2010) also recommended an agent-based gaming solution for practical rehabilitation. Such games while being fun and stimulating must consider and incorporate variables such as expertise and motivational capacities of rehabilitation practitioners. The end result is that the games are usually more complex than the mass-produced ones which can be too challenging and not suit the need of the patients. Reports of patient compliance and progress are sent to healthcare specialists for evaluation and consideration. The gamification technique is being further improved to ensure engagement and equipped to monitor patients as well as encourage smart learning mechanisms. (Li et al., 2016).

4.1.3 Robotic therapy & Telerehabilitation overview

Since intensive and repetitive therapies give positive feedback regarding motor recovery, it is reasonable to look for a possible way to conduct those therapies automatically and precisely. A robotic system is a good fit for the job due to its mechanism. Nevertheless, robotic rehabilitation is not a replacement for physiotherapists but a supplement tool for them.

When it comes to the upper limbs, the rehabilitation robotics can be classified into two groups: End-effector (e.g. MIT/IMT-Manus (Hogan et al., 1992), MIME (Lum et al., 1999), BI-Manu-Track (Hesse et al., 2003) Gentle/S (Loureiro et al., 2003)) and Exoskeleton (e.g. REHAROB (Abrahams & Geschwind, 2008), ARMin (Nef & Riener, 2005), L-Exos (Montagner et al., 2007)) based systems (figure 4.1). In addition, the

literature states that these systems can be passive, active or interactive. Passive systems are used to force patient's arm to follow a predefined range of motion; passive systems can be moved easily when pushed by the patient due to the mechanical linkages usually used in their designs. Active systems are used to move patient's arm from a determined position to another position using a particular velocity profile. Interactive systems respond patient's input and provide appropriate assistances (Riener, 2007).
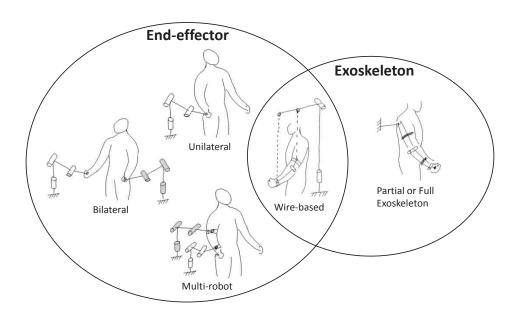
Figure 4.1: Categories of main configurations for upper limb rehabilitation by robot. (Adapted from Loureiro & Smith, 2011)

End-effector systems provide a single end-effector point which the patient can interact with. By manipulating this point, the patient can experience imposed forces of the robot. A single interface is provided for all the forces and measurements therefore these systems have advantage to setup for different body sizes of patients easily (Huang & Krakauer, 2009). Also, end-effector systems can combine two passive or active robots to deliver bilateral therapies; or multiple robots for multi-robot therapies (figure 4.1). On the other hand, exoskeleton systems refer to systems that enclose the patient's arm in a mechanical suit. Because all joints are determined, these

systems can control the orientation of arm. Hence, exoskeleton systems can provide partial or full arm configuration (figure 4.1); and easily to apply and measure forces at each joint. Some systems incorporate both end-effector and exoskeleton approaches to provide a better support for upper limb rehabilitation. For instance, in Gentle/S system (Loureiro et al., 2003), it combines a wire-based technique (figure 4.1)-where wires are attached to a splint or an exoskeleton to provide both passive gravity and active height controlling- with an end-effector system using a unilateral.

Telerehabilitation is offering rehabilitation services over telecommunication networks and the internet. In older adults, it is most desired in the patient environment rather than in hospitals or clinics. This is because such practices are of great benefit not only to the patients but also family members, caregivers, researchers, and clinicians.

The reason why telerehabilitation is encouraged especially in the older adult population is due to the significant strain on resources of healthcare institutions. In an era where life expectancy is high, there is an increased demand for medical and technological support needed to extend the number of active years and disability-free period. Despite the increased life expectancy, older adult impairment is also on the rise mainly due to a reduction in mobility and increased vulnerability to disease and other accidents. This usually leads to post-intervention rehabilitation which requires a long period of therapies and thus, a significant increase in public health costs as well as reduction of the quality of service as resources become scarce.

However, methods such as telerehabilitation can help maintain the balance between the quality of care and increased patients. For instance, patients that require monitoring can be telemonitored with systems that automatically transmit the data collected from their domestic environment to health clinics. Traditionally, telemonitoring is limited to passive observation of patients' behaviours. But for an activity such as telerehabilitation, the scope would have to be expanded as patient

adherence and acceptability of rehabilitative practices must be actively improved, overcoming pitfalls due to motor (e.g., endurance), nonmotor (e.g., fatigue, pain, dysautonomia symptoms, and motivational), and cognitive deficits.

Thus, Rodriguez et al. (2015) defined rehabilitation as "the application of telecommunication, remote sensing, operation, and computing technologies, to assist with the provision of medical rehabilitation services at a distance." Extensive adoption of telerehabilitation systems is beneficial to healthcare providers and patients (Calvaresi et al., 2015). From an economic perspective, Mozaffarian et al. (2016) estimated the total cost of strokes in the US to be 34.3 billion dollars in 2008, rising up to 69.1 billion dollars in 2016. While this is not accurately quantifiable due to inadequate data, Mutingi et al. (2015) presented "inevitable advantages" as (i) significant cost-saving advantage mainly due to the reduction of specialized human resources, (ii) an improvement of patient comfort and lifestyle, and (iii) enhancements of therapy and decision making processes. Morreale et al. (2007) further state that the most appreciated benefit will be the increase of adherence to rehabilitation protocols.

Telerehabilitation requires new technologies and numerous architectures to adequately serve user needs but due to technological and technical limitations, physiotherapist needs have not yet been wholly satisfied. For instance, it cannot offer the same behaviour to users with different conditions or in accordance with environmental conditions. There is a need for system evolution and adaptation to users' needs to fill this lacuna.

Telerehabilitation is characterized by a fragile equilibrium between the environment, devices, and users. On one hand, features such as self-adaptation, autonomic self-management, extendible knowledge, ubiquity, and adaptability, have been shown to be essential in promoting usability as well as actual practices thereby leading to the relevance of systems relying on a Multi-Agent approach in assistive and healthcare settings. Alternatively, the ability to provide a bounded response (predictability) is critical in

guaranteeing the appropriate feedback and safe on-time coaching (reliability). These two are strong features of real-time systems. Therefore, a perfect solution will require a combination of both such as multi-agent real-time compliant systems and agentified real-time systems.

Telerehabilitation is required even in countries with exceptional and capillary healthcare systems and mainly focuses on older adults and patients in rural areas where medical centres are not accessible. However, different approaches have been suggested based on the patient's condition and medical needs. In the opinion of Carignan et al. (2006), the major types of telerehabilitation interactions are: (i) unilateral: patient and therapy are examined with a time-delay; (ii) interactive bilateral: patient and therapist communicate through a virtual environment (e.g., video, virtual, and augmented reality) but without a direct force-feedback in either direction; (iii) cooperative bilateral: therapist and patient communicate directly with each other, remotely but with video, force, and kinesthetics feedback.

Due to inadequate studies regarding the patients, the interpretation of a particular group is limited. However, the recovery period usually lasts about six to eight weeks and it can follow a traumatic experience (e.g., fall of a fragile older adult) or surgical intervention (e.g., joint replacement). The Engineer works alongside physicians, physical therapists, and occupational in therapists developing telerehabilitation solutions, (Mikolajewska et al., 2011) With scientific improvements, telerehabilitation covers both those that are both physically and cognitively impaired. Solutions are designed and customized to relieve pain, maintain or slowly recover physical and/or mental capabilities.

The therapies mostly provided are occupational, physical/motor-function, and cognitive/neurological. Telerehabilitation systems can cope with four main activities depending on focus and point of delivery (i) training, (ii) counselling, (iii) monitoring, and (iv) assessment. Haily et al. (2011) listed twelve clinical categories supported by telerehabilitation systems, they include cardiology, neurology, cancer-related, speech disorders, urology,

rheumatology, pulmonary, chronic pain, orthopaedic, morbidity, child obesity, age-related co-mobility.

In conclusion, most of the rehabilitation practices can be turned into unassisted sessions which will be beneficial in numerous ways such as (i) speeding up the follow-up, (ii) improving the healing process, (iii) shortening the hospitalization, (iv) lowering the costs for both patients and health structures, (v) enabling continuous monitoring, (vi) providing equitable access to rehabilitation services, and finally (vii) supporting the technological advancement in telemedicine.

4.2   Category of telerehabilitation applications

Available technology has encouraged the development of various telerehabilitation techniques and methods. Applications have been designed to perform these techniques, and these applications can be grouped based on their functionality, which has been described by Calvaresi et al. (2019). The categories include:

- Video analysis – includes stereoscopic cameras and image processing algorithms;
- Wearable technology – includes embedded devices and inertial sensors supported by kinematic algorithms;
- Robotics – focuses on in monitoring and motivation involving humanoids and basic robots;
- Distributed sensing – includes monitoring and reasoning by exploiting environmental sensors;
- Gamification – includes coaching techniques and persuasive technologies.

Although there is an availability of solutions, telerehabilitation systems still have to contend with users' acceptance with factors such as cost, setup, maintenance, ease of usage, effectiveness, safety, etc. determining whether a solution is accepted or refused. Given the number of very similar solutions, it is obvious that what is needed by physiotherapists and patients is yet to be achieved.

4.2.1 Video-based systems

Systems that support both cognitive and motor stroke are one of the current trends. Using video-based technologies in the form of virtual reality and video-elaborations, an application has been integrated into traditional rehabilitation practices with encouraging results

Iarlori et al. (2014) suggested a computer-vision based system to be used by patients suffering from Alzheimer's disease. They stated that the diagnosis of the illness stage can be determined by monitoring the patient in his private environment and analysing the data from personal care activities. Noticing any action listed in the Direct Assessment of Functional Status (DAFS) index and detecting performance anomalies signifies dementia stage. The author further used Microsoft Kinect to gather data from actions such as teeth brushing, hair grooming and tracking gestures. The collected data is analysed and once an irregular behaviour is spotted, the patient can receive immediate support.

Camirao et al. (2017) proposed an investigation into how Virtual Reality could be used to deal with the needs of a particular class of patients. Their study was an assessment of the recovery of a cognitive-motor VR training with personalized tasks and positive stimuli, compared to time-match orthodox rehabilitation in the subacute phase of stroke. For the study, a VR system named 'Reh@Task' for training attention, memory, and movement was developed. However, no clear evidence showing significant effect with respect to standard rehabilitation model have been identified yet for, especially for patients with major cognitive impairment. In order to find out ways in which a given stimuli in a specific virtual environment can affect the performance of tasks and overall patient recover. Oliver et al. (2016) created a system based on cognitive and motor rehabilitation that was targeted at aging individuals. The system which majorly focuses on Multiple Association, Categorisation and Pair Association presents a deliberate and extensible Rule Authoring component, that due to the diverse cognitive injuries, offers a substantial number of possible exercises to treat them.

4.2.2 Wearable-based systems

This approach offers the most significant information and is widely seen as the potential leader of future improvements in preventive and rehabilitation techniques. This is so because it is more acceptable to most people who don't find it intrusive as camera-based applications. In a study focused on patients in an adult care facility, 93% accepted sensors won their body and considered them non-invasive and without much effect on daily activities.

Bergmann et al. (2011) reported a remarkable consideration of patients in the use of wearable sensors as they didn't want to stigmatize. Physiotherapists are concerned about the small storage which leads to limited recording time, wearability and the reliability of real-time feedback. Smith et al., stated that the present wearable devices successfully used in telerehabilitation can be grouped into 3 categories:

- Microsensors–capture health information by using small, intelligent, and low-energy active devices;
- Wrist devices – monitor health information by using combined sensors, a display, and wireless transmission in a single solution, which is very convenient for common physical activities;
- Smart clothes – capture information by using thin and flexible health sensors, compatible with textiles or made using textile technologies with specific properties (mechanical, electrical and optical).

Cesarini et al. (2014) proposed a customizable solution that assists the therapists and patients from the pre-surgical to the rehabilitation stage. They further suggested a framework comprising of the usage of two inertial sensors and tablet which will accurately observe the knee joint velocity and angular position. In this system, the therapists and doctor can set the exercises and the requirements such as the number of repetitions, amount of steps and angular extension essential to the therapy. When doing the exercises, the system provides the patient with real-time visual feedback on the tablet and assess his performance at the end of the session. They also performed another study on a real-time feedback system of aquatic-space

actions relying on the 'sonification' procedure. This system is made up of pressure sensors placed on the dorsal and palmar sides of the swimmer's hand with a waterproof embedded system placed on his back. The swimmer's motion produces pressure signals which are processed by the system and provided in real-time to both the swimmer and his trainer. Such a system can be used for rehabilitative activities and has been presented in a specialized conference on aquatic therapy where the therapists generally accepted it as a promising tool for training and recovery of motor and coordination functions.

4.2.3 Robotic-based systems

Robotic devices have contributed to rehabilitation procedures through automation. This has helped to reduce the number of training and rehabilitative sessions of upper and lower extremities because unlike traditional methods, automated robot solution can obtain more numbers of exercise repetition. Task-oriented repetitive movements are known to lead to an improvement in muscle strength and movements for patients with neurological injury. Eriksson et al. (2005) designed an automated assistive mobile robot that monitors, encourages and reminds rehabilitating stroke patients. Moving independently, it observes any extreme activity in rehabilitation and reminds patients to stick to the program where they transgress. Their experiments involved post-stroke patients and the suggested approach received positive responses about the very active and animated robot behaviour. The control system used is behaviour based and categorized as pre- and post-condition to provide real-time feedback.

The challenge to develop a rehabilitation system beyond the hospital stay is that the robotic system must be affordable. Therefore, such systems often use devices with fewer active degrees of freedom (DOF) combined with games as a part of therapy, and/or combining active and passive joints (Toth et al., 2004). The first robotic rehabilitation system using telemedicine and haptics is the Java Therapy system. It consists of a website containing game-based therapies with a force feedback haptic joystick which can resist or assist the user. The arm function of the patient can be

improved through these therapies. Also, users can access their own performance report as well as rehabilitation progress via website interface (Reinkensmeyer et al., 2001). The limitation of this system is that the device has very limited workspace which limits the upper arm range of movements it can effectively support.

The Rutgers Master II system provides therapist a tool to modify therapy configurations remotely while transferring the therapy to patient place (Popescu et al., 2000). This system provides assistance to opening and closing of the user's fingers but does not assist with arm movements. Bach-y-Rita et al. (2002) developed a computer-assisted motivating rehabilitation (CAMR) system, which can be used in the home environment. The system integrated a pong game with a mechanized handle and has an ability to quantify impairments. Other examples for home-based environment systems include TheraDrive (Johnson et al., 2004) and TheraJoy (Johnson et al., 2007), these systems work together via a single software interface called UniTherapy (Feng et al., 2004; Feng & Winters, 2007) using low cost joysticks and wheels to deliver different therapy sessions via custom and/or commercial games and tasks.

All systems mentioned above have the option for the therapist to observe the exercise and interact with the patient remotely in real-time. Another interesting and feasible telerehabilitation approach is a system implemented with the MIT-MANUS robot that combines a tele-cooperation with teletherapy (Carignan & Krebs, 2006). In this system, the therapist can develop various scenarios where therapists and patients work together in a shared virtual environment to perform a particular exercise, such as reaching and grasping an object. Loureiro et al. (2006) used the same combination with a patient-to-patient paradigm to evaluate the system in terms of the influences of this type of cooperation to enhance patient motivation, their experiences through the shared tasks, the most valuable and interesting participants.

Another population can be beneficial from a robotics-based system that is people with autism. Recent research has focused on developing joint attention skills for children with autism (Whalen & Schreibman, 2003; Jones et al., 2006; Martins & Harris, 2006). Nevertheless, these studies mostly relied on teaching children skills (usually limited to one skill at a time) rather than considering the naturalistic play settings. In these studies, often target skills are taught to the children participating in the study, which presents with limitations in terms of the generalisation of those skills applied to other people or context. There are several reasons that could be used to explain why target skills are not generalised. For instance, the skill might be taught in a structured and thus predictable context, consequently the child may find it is difficult to perform it in a more natural setting or with another person; or the skill might be unsuitable for the child or more specific, the child may not be ready yet to learn the skill (Kasari et al., 2010). Thus, there is a need to develop an intervention that could be applied in a normal circumstance and deliver a playful way to teach autistic children joint attention skills.

Several studies have shown that technology-based interventions were beneficial for children with autism: from the conventional methods such as using auditory and tactile devices (Taber et al., 1999; Coyle & Cole, 2004; Taylor & Levin, 1998, Taylor et al., 2004), computer-based interventions (Silver & Oakes, 2001; Heimann et al., 1995; Rehfeldt et al., 2004; Bosseler & Masaro, 2003) to the more innovative ways such as virtual reality and robotics (Strickland et al., 1996; Max & Burke, 1997; Dautenhahn & Werry, 2001; Diehl et al., 2012; Ricks et al., 2010; Scassellati, 2005; Bekele et al., 2012).

The use of robotics for aiding people with autism has been increased rapidly in the last few years (Scassellati et al., 2012). However, unlike robotic rehabilitation for people after stroke, which emphasises on physically interaction, robotic interventions for individuals with autism mostly focus on developing and implementing the assistance to the users through social interaction. Hence a socially assistive robotics (SAR) system for autism

therapy would consider multiple social aspects such as emotional expressions, user engagement, communications, and user's behaviours in order to deliver safe (nonnegative effect on user's emotion) treatment which must also be engaging and beneficial for social communication skills.

There is no consistent design trend for the appearance of robots for autism since it could be varied in many levels of anthropomorphism (figure 4.2): humanoid (e.g. Nao, Milo, Kaspar, Bandit, Infanoid), animal-like (e.g. Pleo, Aibo), cartoon-like (e.g. Muu, Tito, Keepon), machine-like (e.g. bubble blower), or robot with non-biological form (e.g. Roball). The reason for this variation is because it is very difficult to decide how life-like the robot's appearance should be. Whereas a life-like form such as a humanoid robot might help to transfer the social skills that the individuals with ASD learned in human-robot interaction to the similar skills in human-human interaction; the less life-like robot, on the other hand, could reduce the distraction as well as the complexity of the stimuli which results a better focus attention on particular social skills (Scassellati et al., 2012). The usual approach applied by most of research groups is to design a robot with attractive/interesting appearance which could interact with the autistic user directly in a human-robot interaction model i.e. the robot can generate a range of actions that robot and human could engage in together. In this type of interaction, the robot might act as a role model and guide user to follow a sequence of activities to learn social behaviour e.g. asking a child to mimic the robot to perform a spinning task (Michaud et al., 2005), the robot playing with the child in predetermined scenarios (Duquette et al., 2008; Ferrari et al., 2009), or simply moving autonomously allowing the child to interact freely (Feil-Seifer & Mataric, 2011). It can also be a toy which mediates social behaviour between the users (Stanton et al., 2008; Robins et al., 2005). In some occasions, it encourages autistic users to express their emotions (Kozima et al., 2005).
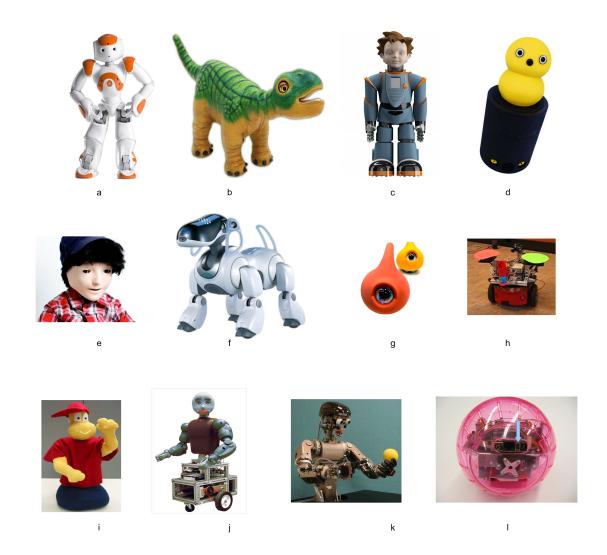
Figure 4.2: A selection of applied robotic therapy for people with ASD: *(a)* Nao; *(b)* Pleo; *(c)* Milo; *(d)* Keepon; *(e)* Kaspar; *(f)* Aibo; *(g)* Muu; *(h)* Bubble Blower; *(i)* Tito; *(j)* Bandit; *(k)* infanoid; *(l)* Roball

There is no surprise that most of robot-mediated interventions for autism up to date (as shown above) lack of method to collect quantitative data. As a result, studies involve the effect of robotic intervention for ASD usually only produce reports based on qualitative data. Although qualitative reports are important and useful, it is still insufficient to generalise the robot effects on therapy for ASD without quantitative analysis (Scassellati et al., 2012). Some research groups have undertaken the difficult task of extracting quantitative data by analysing the recorded videos frame by frame e.g. taking note of the time spent when the user looking at the robot (Duquette et al., 2008; Kim et al., 2012; Stanton et al., 2008; Feil-Seifer et al., 2009; Wainer et al., 2010). This process is time-consuming and inefficient to analyse complex data thus, making it more difficult to develop more individualised and powerful interventions (Sandall, 2005; Diehl, 2011).

4.2.4 Gamification-based systems

Jacobs et al. (2013) realised a game that aids arm-hand rehabilitation for stroke survivors. With the simple goal of making the training fun and effective, the game which is task-oriented requires the gamer to manipulate common objects and raises its difficulty level based on patient performance. Within a week period, the authors evaluated both the physical and cognitive abilities of two patients suffering from stroke. Simmons et al. (2014) studied a group of veterans with motor impairments diagnosed with acquired brain injury. Exercise games called PreMotor (PEGs) was used to observe their upper-limb motor function (manual muscle, goniometric range of motion, and dynamometer assessments) and executive functioning (testing cognitive functioning). At the end of the intervention, results show a clinically relevant improvement in participants regarding shoulder, elbow, and wrist strength. This shows the success of computer-based simulation which could reduce the need for physical therapy with medical personnel. However, for this to happen. There is need for further research to determine which technologies are best for which intervention, this is so because telerehabilitation systems operate in very dynamic environments with

mutual interdependencies and complex distributed controls and have to face context-rich situations, uncertainty and deal with distributed sources of information. Classic methods though could be effective lack vital characteristics including compatibility, coordination, collaboration, and communication (Rodriguez et al., 2015). Thus, they end up being abandoned or require integrative upgrades which could cost ridiculous amounts to function effectively. Miranda et al. (2003) listed some of the common incompatibility problems such as data formats (e.g., storing format of 3D images) and different communication protocols. Thus, studies like Bergenti et al. (2010) consider multi-agent systems (MAS) as a suitable "technology" to realize such applications.

It is noteworthy to restate that MAS consist of several agents that interact with one another for the allocation of resources, computational and decision-making tasks. These agents communicate using the network interfaces which allow them to reach a common decision or private goal (e.g., consensus, synchronization, monitoring of health parameters and surveillance). It is for this reason that MAS has been adopted in the rehabilitation solution seeking to manage physical and cognitive phenomenon and providing specialized models and equipment.

4.2.5 Other proposed solutions

In order to create a platform for interactive learning, Su et al. (2012) designed an ontology defining vocabulary, entities and their relationship in rehabilitative medicine. The inference engine was used so that existing data can reveal new knowledge having an "asserted model" as input and "inferred model" as output. The work of Brugués et al. (2016) is another example of agent-based reasoning. The author faced two major difficulties: (i) scalability – by distributing the reasoning on mobile devices, and (ii) penalization by aiding medical staff with a graphical application that simplifies the definition of temporal patterns of physiological values. Liao et al. (2009) dealt with the security and reliability of an agent-based platform for telemonitoring. Lai et al. (2004) suggested a study involving a

community rather than the traditional one patient. The authors assessed the effectiveness of rehabilitation techniques for post- or chronic- stroke survivors involving video-conferencing solutions and praised the feasibility, efficiency, and acceptability of telerehabilitation in community-dwelling stroke clients, recording improvements in both physical and psycho-social wellbeing.

4.3 Network failures affect distributed VR-haptic based system

The network limitations due to the long-distance communication between sites via Internet could affect the collaboration in a virtual environment. The network performance is evaluated through the impairments of different metrics. Marshall et al. (2008) identified those metrics as: network delay, jitter, loss and throughput.

- Network delay: This kind of network impairment is inevitable particularly in a large network environment such as Internet. The electrical signal needs a certain time to be propagated to a transfer medium. Theoretically, the latency range for data transfer from the UK to the USA is expected from 80 ms to over 100 ms (Jay et al., 2007).
- Network jitter: Jitter is defined as the variance of arriving packet's time. It is usually caused by a heavily congested network and it adversely affects a task requiring consistent rates such as predicting routine movements (Gutwin, 2001). Even a small amount of jitter could cause severe impact on distributed haptic based system (Yap & Marshall, 2010). However, it can be minimized by either improving network Quality of Service or using data buffer (Gutwin, 2001).
- Network loss: loss is measured by the percentage of packets lost to the total number of packets sent. The impact of loss varies depending on the architecture of the system e.g. client-server or peer-to-peer,

and/or the network protocol such as UDP or TCP (Yap & Marshall, 2010).

- Network throughput: Throughput is defined as the quantity of transmitted data per unit time. It is strongly related to the network delay, jitter and loss. For instance, if the network protocol is UDP, the loss occurs when the throughput happens i.e. transmission rate exceeds the bandwidth. On the other hand, if the protocol is TCP, the throughput causes congestion, as a result, TCP algorithm would react by reducing the transmission rate which leads to the network delay (Yap & Marshall, 2010).

The next section introduces some well-known methods to overcome the above issues of the network failures.

4.3.1 Delay concealment methods

Dealing with network failures has been a crucial challenge for the field of robotic teleoperation for several decades. A lot of methods have been conducted to reduce the effect of network delay however each of them still has limitations hence does not deliver the desired result. Table I describes four most common techniques that have been used widely in the field:

Table I: Four most common concealment methods for network failures

Group	Type	Description	Positives	Negatives
Smith and Jensfelt (2010) Natarajan and Ganz (2008)	Predictor	If a lost data packet is found, it will be sent to a predictor unit. This unit is developed using a predictor algorithm which predicts the missing data based on previous received packets or human movement model such as minimum jerk. The remote client will then render haptic feedback using given result.	This method significantly reduces the delay caused by network's limitation. In addition, predictor algorithm could be changed or optimised to give a better result.	This method will cause a deviation between the receiver and the source. The predicted packet is always different from the original value. As a result, it may lead to the incorrect interaction between users as well as raising unexpected safety issues.
You et al. (2007) Wongwirat and Ohara (2006)	Synchronization Control Schemes	By using delay synchronization module at the server side and each delay module at client side, it would buffer incoming data thus delay haptic rendering at each client until all clients are synchronized	Since all clients can obtain the same haptic display as the server without jolting and buzzing, the outcome force feedback is reliable therefore ensuring the operational safety.	This method highly depends on determining the optimum buffer size of incoming data which could be another difficult challenge. For instance, if the buffer size is low, haptic data will be

				lost and causes an unreliable output. On the other hand, if the size is too big, it will add an unnecessary system delay which slows down the response from server to client.
Guo et al. (2011)	Data Compre ssion	The data compression algorithm divides haptic data streams into subsets based on human haptic perception. The number of these data subsets will be reduced using a geometric distance approach. Each data subset is also fitted by a quadratic curve to improve approximation precision and only coefficients of those quadratic curves will be sent to the destination instead of	A large amount of haptic data could be reduced using this technique. Hence it is extremely useful for a system which requires the transmission of voluminous haptic data. Moreover, it can combine with other technique such as a predictor to eliminate the latency even more.	This method is not very useful for the transmission of a small amount of haptic data. In addition, using this method on its own without combining with other techniques does not help to resolve the delay caused by network limitation.

		the original haptic data.		
Bouker che et al. (2007)	Multiple protocols	This method is a combination of multiple protocols such as Synchronous Collaboration Transport Protocol (SCTP), the Selective Reliable Transmission Protocol (SRTP), the Reliable Multicast Transport Protocol (RMTP) and the Scalable Reliable Multicast (SRM) in a single system. The combined protocol has a multicast tree to avoid congestion and delay issues. It also ensures data reliability using multi modes of transmission	By combining multiple protocols, this method can take advantages of everyone since those protocols have different features. As a result, the data transmission is reliable, the delay is minimized, congestion is avoidable, and synchronization is achievable.	Although this method seems to be an ideal to deal with network impairments, it still requires the multicast tree algorithm to work reliably which is also a difficult challenge.

4.4 Chapter summary

This chapter introduces multiple state-of-the-art therapies and methods in telerehabilitation robotics.

The advantages of telerehabilitation robotics over conventional therapy are significant cost-saving, an improvement of patient comfort and lifestyle, enhancements of therapy and decision making processes, and the increase of adherence to rehabilitation protocols (Mutingi et al., 2015; Morreale et al., 2007). However, due to technological and technical limitations, there is a need for system evolution and adaptation to offer the same behaviour to different users and conditions. Thus, the research presented in this thesis is highly relevant to the field as it aims to understand better user's behaviour which helps to modelise telerehabilitation system's feedback and support to the users.

This chapter also explains how robotic-based technology can support social aspect of the practice sessions which potentially help both people with stroke and people with autism since they are sharing the same social need to connect to other people although they are very different populations. Chapter 5 expands this further by introducing some benchmarks to evaluate a socially assistive robotic system and how to design an effective system based on these benchmarks. This chapter also introduces a category of different telerehabilitation applications (Video analysis, wearable technology, robotics, distributed sensing, and gamification). The framework introduced in chapter 5 supports all these applications.

There are four well-known methods in the literature to conceal the negative effects of network failures introduced in this chapter. Two of these methods (predictor and synchronisation control schemes) have been applied in the experiment in chapter 8.

Chapter 5: Design of the haptic framework supporting group interactions

Chapter 5 introduces socially assistive robotics (SAR) field and explain why this non-physical contact approach can help post-stroke or other physical rehabilitation. This chapter shows the taxonomy of SAR and some benchmarks to evaluate a SAR system. It also presents the design of a haptic framework that can support SAR field and group interaction. The framework is designed to support multiple haptic and external devices, can be easily integrated with other telerehabilitation systems and have functionality to manage patients' data and training session remotely.

5.1 Socially Assistive Robotics

5.1.1 Introduction

The most common use of assistive robotics is related to the robot's functionality to assist physical interaction for people with physical impairments. Examples of the assistive domain include post-stroke rehabilitation (Burgar et al., 2002; Dubowsky et al., 2000; Harwin et al., 1988; Loureiro et al., 2007; Kahn et al., 2003; Mahoney et al., 2003), wheelchairs and mobility aids (Aigner & McCarragher, 1999; Glover et al., 2003; Simpson & Levine, 1997; Nisbet et al., 1995), post-operative cardiac care (Kang et al., 2005), cognitive rehabilitation for traumatic brain injury (Christiansen et al., 1998; Grealy et al., 1999).

However, in the past few years, assistive robotics field has been expanded to support not only contact interaction but also non-contact interaction. Fong et al. (2003) have used the term socially interactive robotics to describe the social interaction between human and robot which is distinguished from traditional human-robot interaction. According to Feil-Seifer & Mataric´ (2005), socially assistive robotics (SAR) is the intersection of assistive robotics and socially interactive robotics. This particular field of robotics focus on the improvement of social interaction aspect of the robot rather than physical assistance (Wolf et al., 2005; Feil-Seifer et al., 2007). Constraint Induced (CI) therapy introduced by Winstein et al. (2003) has been recognised as an effective rehabilitation method for people after stroke. In this therapy, there was no physical contact between the patient and therapist. Instead, therapist only coached and reminded the patient to use their hemiplegic limb(s) during the training session. The result from CI therapy was promising since patients were more engaged to do the exercises longer, generalised motor skills better and had useful behaviour patterns (Winstein et al., 2003). This type of therapy has encouraged researchers in SAR field to apply the same non-contact method for post-stroke or other physical rehabilitation with the help of robot technology. For example, Mataric´et al. (2009) conducted a study on patients after stroke and mild traumatic brain injury using a robot to monitor and coach

users to perform a simple reaching shelve task. The positive results from this study and similar studies (e.g. Kang & Mataric′, 2005) show that SAR field has the potential to enhance the quality of life for people with special needs.

5.1.2 Taxonomy of SAR

Fong et al. (2003) have defined the taxonomy of socially interactive robotics as follows: *(a) embodiment, (b) emotion, (c) dialog, (d) personality, (e) human-oriented perception, (f) user modelling, (g) socially situated learning, (h) intentionality.*

Feil-Seifer & Mataric′ (2005) completed the taxonomy of SAR by adding following properties to the above taxonomy:

- *(i) User population:* elderly people, individuals with physical impairments, individuals in convalescent care, individuals with cognitive disorders, students
- *(j) Task examples:* tutoring, physical therapy, daily life assistance, emotional expression
- *(k) Sophistication of interaction:* speech, gestures, direct input
- *(l) Role of the assistive robot:* caregiver, social mediator, companion in nursing home, etc. (defined by the nature of the task and user population in which the robot assisting with)

5.1.3 Benchmarks for evaluating SAR

Feil-Seifer et al. (2007) proposed some benchmarks for SAR evaluation based on the existing methods in psychology, anthropology, human-robot interaction, etc. (Wainer et al., 2006; Kahn et al., 2007; Baker & Yanco, 2005; Harnad, 1989; Cowie et al., 2001; Busso et al., 2004) Their proposed benchmarks can be described as follows:

Robotic Technology:

- Safety: This is an important aspect not only for SAR but also for any robotic system. Basically, this benchmark asks the question: how safe is the robot for both itself and its user? For instance, can the robot avoid obstacles when navigating or guiding people? Can the robot protect the user if unexpected situation happens?
- Scalability: The ability of the robot to work effectively in different environments and user populations. Can the robot work the same way with real users (people with special needs) as it works with healthy users? How well it performs outside controlled environments such as lab or hospital?

Social Interaction:

- Autonomy: The ability of the robot to work well on its own for a predefined task. For example, can the robot perform expected activities to assist users? Will the users or therapists trust the robot that it can perform effectively?
- Imitation: This benchmark questions whether robot's behaviours match user's expectations. In other words, can the interaction between the user and the robot correctly reflect the impression of robot and user's capabilities?
- Privacy: In some circumstances (e.g. embarrassing environments), robot may help to increase the privacy of the user rather than human therapist. Thus, it is important to test whether the better performance of the user when interacting with the robot relating to their perceive of privacy? Will the privacy affect user's satisfaction?
- Understanding of domain: There is a crucial aspect for SAR - the robot can understand user's behaviour and adapt itself correspondingly for better assistance. Do the robot's adaptive behaviours help to improve user's performance?
- Social success: Does the SAR system achieve its social goal? For instance, is a playful activity generated by the robot actually playful?

- Impact on user's care: Does the SAR actually give a better result comparing to human therapist doing the same training/recovery task? How about the cost's effectiveness? Is the robot more cost effective than human? Does the robot make the therapy available which is not possible before with human therapist?

- Impact on caregivers: Does the SAR improve caregiver's job? Can the caregiver work well with the robot?

- Impact on user's life: Does the robot improve user's quality of life based on their opinion?

5.2 Framework

This thesis proposes a haptic framework that can enable group interaction via a network connection. The purpose of such framework is that it can support a full cycle of patient management remotely (e.g. monitoring, giving instruction, setting practice session, and collecting data), can be easily expanded and integrated to other robotic telerehabilitation systems, and can be applied in different social settings (e.g. home, school, gallery, etc.).

5.2.1 Framework architecture

This framework introduces a new approach for SAR literature. Instead of using a robot to coach and monitor user's behaviour, it applies haptic robots as mediators that allow multiple users with the same conditions to interact to each other. In other words, it allows group interaction via one or multiple haptic robots in the same environment which has never been done before in SAR field.

The existing framework design is based on three-tier software architecture. The framework has been developed using C++ programming language and object-oriented design. This allows the framework to be reusable and expandable for the future development and improvement. At least two users could interact with the application created by the framework

simultaneously (see figure 5.1). The presentation tier provides feedback to the users through several services: visual renderer for the visual feedback and environment simulation, sound renderer (integrated with Max/MSP) for the audio feedback and haptic renderer for haptic feedback (e.g. force and/or tactile feedback, vibration, etc.).

The framework enables a client-server type to maintain the safety of interactions between multiple participants since their practice sessions need to be supervised. Therefore, application logic tier is run on a server with logical services: Haptic APIs will have two important haptic components such as collision detection and force feedback calculation - these components are adapted from Chai 3D haptic library. The framework integrates external APIs to control other useful sensors e.g. Kinect (OpenNI/NITE), camera for AR tracking (ARtoolkit), Galvanic Skin Response (GSR) sensors for measuring emotion stimulus (e-health library for Arduino), Force-sensing resistors (FSR) for obtaining application forces (self-developed). Those sensors enable the framework to deliver collaboration tasks in the real world with data logging and measuring functionalities. General controller module of the framework is used to implement internal logic of the system and the access to store and retrieve data from database (data saved as Microsoft Excel files).

The network functions have also been added to the framework to enable two or more clients working in a same virtual environment via both local and Internet networks. Users can choose different network protocols to connect to each other (see figure 5.2 and figure 5.3). However data transmission still can be optimised based on the delay concealment solution suggested by You et al. (2007) – by using a delay synchronisation module at the server side and each delay module at client side, it would buffer incoming data thus delays the haptic rendering at each client until all clients are synchronised.

The framework also has two important functions to compensate poor network conditions to maintain smooth interactions between participants:

- A predictor to guess user's intent and help them to finish the task when the network condition is poor. More specific discussion of this module will be later in chapter 8.

- A function to test different network conditions. This function will help the system to decide when to enable the predictor. The network condition to ensure the smoothness of haptic interaction could follow the suggestion by Buttelo et al. (1997) as to simulate objects with the ideal stiffness of 1000 N/m, the network delay in their system must be less than 5 ms. However, more tests need to be done to select the optimal thresholds.
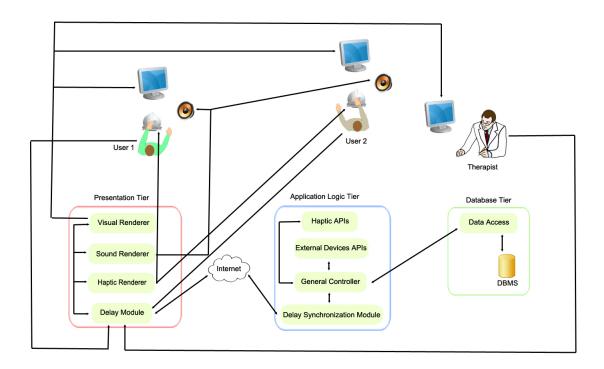
Figure 5.1: Overview of framework architecture. Three tiers design for future maintenance and expandability – presentation tier includes all visual/ sound-related components, haptic renderer, and delay compensation module. Application tier includes all logic APIs and delay synchronisation algorithm. Data tier includes all data storage/retrieval methods.
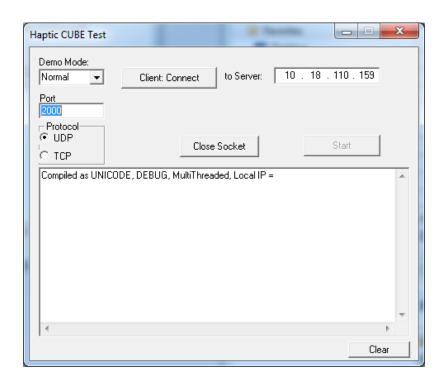
Figure 5.2: User interface of the client application
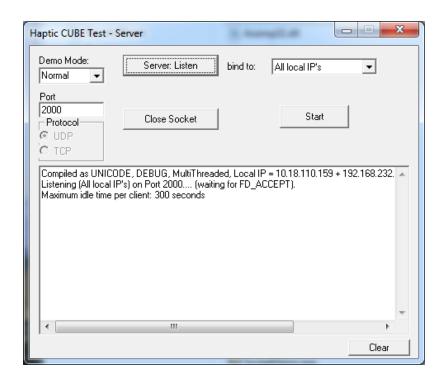
Figure 5.3: User interface of the server application

5.2.2 Functionality of the framework

- Support low-cost haptic devices (e.g. Novint Falcon and Phantom Omni) and other devices that support UDP protocol. This functionality enables the flexibility of the framework, it allows to setup different types of practice/ training session based on the haptic devices.

- Integrated multiple open source APIs to support different external devices (Kinect, AR cameras, sensors, Arduino, etc.). This functionality allows to collect extra information/ data from participants thus it could potentially make examination and evaluation of patient management easier.

- Network function to support remote haptic group interaction (support TCP/IP and UDP protocols in a local network). This functionality also enables participants to work together in their own comfortable places. The therapist can also monitor the whole training process remotely.

- Synchronised with Unity game development engine to generate 3D graphical scenes and environments. This functionality enhances graphic quality of the virtual environments therefore improves user's experience.

- Synchronised with Max/MSP software to support 3D sound and effects. This functionality improves sound quality of the applications, combined with the enhanced graphic, it could encourage participants to spend more time with their task.

- Data collection and storage. All data collection can be done remotely and stored securely. The Therapist or research can also access data easily for analysis.

5.3   Chapter summary

This chapter introduces the SAR field in general with different use cases and benchmarks. It also proposes a haptic software framework which integrates multiple open-source components and modules to be able to deliver a variety of applications for telerehabilitation. Some benchmarks introduced in this chapter are also be used in chapter 6 to test out the capability of the framework.

The framework was also implemented in various ways and presented throughout this thesis:

Built an application for a group interaction task. This application did not involve any sound or visual feedback. The application had a function to track participants' movements (using a 3D camera) and transferred these movements to control a haptic robot (Novint Falcon – chapter 6 – section 6.1).

Built two applications supporting haptic devices (Novint Falcon and Phantom Omni) with only sound feedback and without any visual feedback (These two applications are different from each other; more details can be found in section 6.2 and 6.3 in chapter 6).

Generated a haptic collaboration system which can enable a pair of participants working in the same environments (real or virtual) to complete a specific goal. The system had AR tracking functionality (using a normal camera), sensors to detect stress (GSR sensors), and haptic feedback from haptic devices (Phantom Omni) (details can be found in chapter 7).

Collected data to create a predictor. This predictor can be used to compensate data loss due to a poor network connection. A test bed application also has been built to test out the performance of the predictor (chapter 8).

Chapter 6: Pilot studies: How working in a group changes participants' behaviours

Chapter 6 presents pilot studies involving group interaction with haptic and sound feedback. Three studies have been conducted in which tasks were generated using the framework introduced in chapter 5 to investigate how people interact to each other in a group or on their own. These studies have two goals: first testing the hypothesis to identify whether group interactions have any advantage over individual interactions in the same task (e.g., can group interaction help to enhance user's engagement and motivation thus encourage user to work longer?) and second, testing the effectiveness of the framework based on some of the benchmarks for SAR evaluation.

The tasks used for these studies have been designed as playful activities that can be applied in any social contexts beyond hospital and clinical environments. Benchmarks used for testing the frameworks were: scalability (can the framework work well in different environments?), imitation (does haptic feedback reflect user's expectation?), and social success (are users engaged when doing the task? Do they talk to each other?).

The results from this chapter have suggested that participants engaged with the interactive experience and interacted with each other in a positive manner. They also may be preferred to spend more time on the task with someone else rather than doing it on their own.

6.1 Investigation on the effect of group interaction and playful activity in user's behaviours: Robotic bells study

This study reports the initial results of an investigation how group interactions re-shape the individual's mental model while interacting with a Novint Falcon robot that plays a bell attached to its end-effector as the user executes three-dimensional arm movements. The author believes that this approach could have a positive impact in the delivery of rehabilitation paradigms that explore the dynamics of group interaction encouraging collaborative play over longer periods of time than otherwise possible with individual therapy sessions.

6.1.1 Material

1.1.1.1   Experimental setup:

The setup consisted of three laptops and haptic interfaces (Novint Falcon), two 3D cameras (Microsoft Kinect) for hand tracking and 3D avatars generation.

Novint Falcon robot and the Microsoft Kinect sensor are commercial devices that did not require any special calibration to get them working correctly

Applications used include the "Duck" demo from the Chai 3D opensource library, the Haptic photobooth application was created using Chai 3D library to allow participants to take and interact with 3D avatars of themselves, and the Hand tracking application to control the robot was programmed using OpenNI/NITE and Novint Falcon libraries.

1.1.1.2   Hand contour and fingertip detection algorithm

In order for the system to track arm movements the user has to wave the hand to the Kinect sensor to activate the tracking application. The application captures the user's movements and transfers it to corresponding positions to drive the 3-DOF Novint Falcon robot. As a result,

the robot will follow user's hand movements and produce sound through the attached bell. The contour detection used in this system is developed based on the border following algorithm introduced by Suzuki & Abe (1985). This algorithm can be described briefly as follows:

1. All pixels of the input image will be processed and marked as 1 – if that pixel belongs to the pattern or 0 – if that pixel is a part of the background.

2. If the pixel (i, j) – i^{th} row and j^{th} column is 1-pixel and all the pixels (i, 1), (i, 2), ..., (i, j - 1) are 0-pixels, then the pixel (i, j) will be the starting point of the border. The value of this pixel is changed to 2. The value of i and j will be increased to move to next pixels

3. If the current following border is between a set of 0- pixels which includes pixel (i, j + 1) and a set of 1-pixels which contains the pixel (i, j), then change the value of the pixel (i, j) to -2. Otherwise, change that pixel's value to 2. After finishing and marking entire border, the algorithm stops. The component of 2 and -2 pixels is the detected contour of the object.

The rough description of hand contour and fingertip detection algorithms:

1. The Kinect sensor captures user's depth image every 50 ms (20 Hz).

2. The depth data of the hand is used to apply threshold and extract hand region.

3. Applying contour detection algorithm described above to detect the outermost contour of the hand region.

4. Approximating the hand contour with polygons. The vertices of convex hull will be detected as fingertips if their angles are small enough.

6.1.2 Methods

1.1.2.1   Study Design
Eight healthy participants (aged between 17 and 30 years) were recruited from Middlesex University to conduct the experiment (maximum we could

recruit at that time). The participants were divided into two equally numbered groups. Each group was involved in three different phases (Figure 6.1).

- Phase 1 (Conventional Haptic Interaction), consisted in the participants interacting with a haptic model of an object displayed on the computer screen via the haptic device by grabbing the end-effector.

- Phase 2 (Haptic Photo Booth), participants interacted in the same way as with phase 1, but this time a Microsoft Kinect sensor was used to capture the user's face and render an avatar representation of the face (visual + haptic). Participants interacted with face avatar via haptic device by grabbing the end-effector.

- Phase 3 (Robotic Bell), participants are instructed to work out as a group how to make the robot play a bell and were given 10 minutes for this task. Information on the different components was given (e.g. the Kinect sensor, the haptic (robot) device, bells) but no instructions were provided on how to attach the bell to the device or that the Kinect sensor only captures arm movements, i.e. the goal is for the haptic device to move the bell while grabbing the end-effector with the hand as on previous phases. Fig. 6.2 shows examples of users interacting with the robotic bell.

All participants were provided written informed consent and this study was approved by Middlesex University research ethics committee on January 12nd, 2012.

Figure 6.2: Single user (left photo) and group (right photo) interacting with robotic bell (phase 3). The robot can only track one participant's hand at a time, but participants were not informed about it.

1.1.2.2   Data collection and analysis

Audio-visual data was collected while the participants performed the three different phases of the experiment. Simple observation analysis was conducted initially to identify individual mental model conceptualizations and on how the group dynamics developed and affected the individual mental models.

1.1.2.3   Results and discussion

As expected during phase 1, participants' focus was on creating rules based on how the device worked whereas in phase 2, it appeared most of the participants (6 out of 8) were more interested in the way they interacted with the haptic face (e.g. level of force penetrating the surface), thus implying a development of skill level that hindered the technology transparent to the user interaction.

The groups in phase 3 employed different strategies. Group 1, took 1min 20s to work out how to attach the bell to the robotic device, with one of the participants taking the lead in this part. Clearly the mental model developed during the previous phase of the experiment was a driving factor as 3 out of 4 participants tried to get the bell to play by grabbing the device's end-effector. Group 2, worked together from onset and almost immediately attached the bell to the device. It was interesting to see that both groups started very soon to work as a team making coordinated movement patterns, some unsuccessful and some somewhat successful. Following several attempts, it was clear that the groups formed the understanding of movements being tracked by the Kinect sensor, but it took several coordinated attempts for them to realize that only one person's arm was being tracked at one particular time.

The interactions were engaging, and all group members took part, some trying to impose their mental models but generally, all seemed to adjust their models to the group interaction. While it was clear from an initial observation that participants enjoyed the task, it was quite extraordinary to discover that each group performed collectively an average of 3,500 movements during phase 3 (10 minutes).

6.2 Investigation on the difference of user's interactions with haptic/audio feedback while they are on their own or in a group: A study with healthy participants.

This study examines a new form of interaction combining haptic and sonic exploration with static visual information from a real painting. Motivated by robotic bells study, and by the educational and explorative value of artefacts, we investigate the feasibility of an interactive painting as a potential tool for the rehabilitation of brain injuries. The study was divided to two experiments: experiment 1 consisted of a series of twelve single case studies with healthy individuals exploring a painting through haptic feedback with/without sonic interaction and assessed using a multidimensional measurement intended to evaluate the participants' subjective experience. The results from this experiment suggest that when exploring concepts of augmented artefact installations with technology (haptics + sound or just haptic), participants seemed to prefer to interact with haptic + sound over haptic. Experiment 2 consisted of twenty-four healthy participants with the similar setup as experiment 1 with a few differences: participants were divided into a group of individuals and a group of pairs, they also interacted with another painting with different haptic feedback and sound. The results from this experiment showed that participants engaged with the interactive installation and executed more movements while exploring the painting in pairs. It appears that the haptic painting paradigm encourages development of analytical skills, imagination, promotes spatial skills realisation and enhances touch/hearing sensory channels.

All participants were provided written informed consent and this study was approved by Middlesex University research ethics committee on July 31st, 2013.

6.2.1 Experiment 1

2.2.1.1 Material

6.2.1.1.1   Experimental setup
The experimental setup (Fig. 6.3 and 6.4) for this study consisted of a PC running Windows 7, a 3-DOF Novint Falcon robot, a plinth (designed for the

robot), two large speakers and a painting. Novint Falcon robot is a commercial device and does not require any special calibration to get it working correctly. The computer ran two separate applications (haptic application to generate and control haptic objects/effects and Max/MSP software to manipulate sounds) that communicated to each other via OSC (Open Sound Controller) messages. Haptic application was programmed using Chai3D opensource library which was reliable and widely used. Max/MSP is a commercial software which is professionally used to produce special sound effects and interactive sound software. Two speakers were positioned to the left and right-hand sides of the user. The paintings represented a solid sphere (ball painting) (Figure 6.3).

The environment was a dark room with a single light projected onto the painting (Figure 6.4). The computer and researchers were hidden from user's view. The robot was placed on the top of the plinth for the user to grab its end- effector and move freely (limited by the mechanical workspace of the robot - approximately 7.9 x 10-5 m3).

Figure 6.3: Subject exploring the painting in experiment 2. Left top: ball painting used in experiment 1. Left bottom: water painting used in experiment 2.
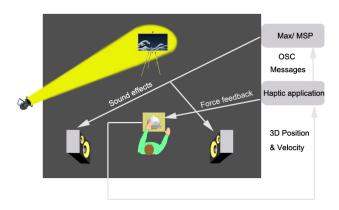
Figure 6.4: Interactive painting experimental system. Participants interact with the painting by grabbing and moving the Novint Falcon end-effector handle.
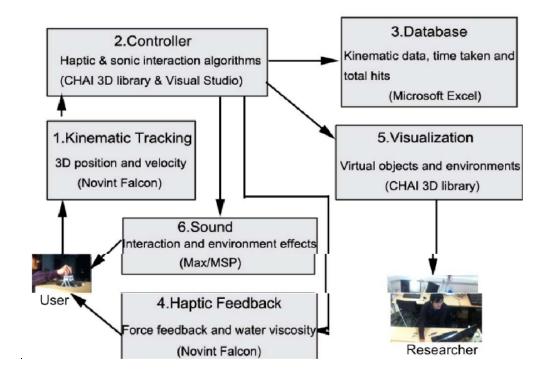
Figure 6.5: A flow chart for the interactive painting system developed.

6.2.1.1.2   The sound effects

The sound effects were implemented using the Max/MSP software package. The haptic application was linked to Max/MSP via OSC messages that were sent/received using UDP protocol and Port number 8000 in a local network. The CNMAT plug-in for Max/MSP was used to receive all

OSC messages that were sent from haptic application. Every time a subject hit the ball, the haptic application sent different signals to Max/MSP, which in turn generated various sounds depending on the position and velocity of the device end-effector. A Pan plug-in was added in Max/MSP to create panned sound effects. The Pan plug-in was used to convert the device's end-effector position into appropriate pan values. As a result, if the participant hit the sphere on the right-hand side, he/she would hear the sound coming from the left hand side. There were 10 different sound effects in this experiment

6.2.1.1.3 <u>God-object algorithm</u>

A haptic sphere was modelled to represent the 'ball painting' and positioned in the centre of the haptic device's workspace. Contact forces were generated based on collisions between the device's end- effector and the surface of the haptic sphere. Forces were rendered based on the God-object algorithm (Zilles & Salisbury, 1995). The God-object is defined as a virtual point that is not able to penetrate hard surfaces. The position of the God-object is updated for every step of the haptic loop. A force generated by a mass-less spring simulation will stop the God-object moving through the surface of a rigid body if a haptic interface point (HIP) - where the God-object moves towards - penetrates the body. The force FS is given by Hooke's law as:

$$F_S = -k\Delta x = -k\left(x_{HIP} - x_{GodObject} \right) \qquad (6)$$

Where k is the spring constant defining the surface's stiffness and Δx is spring's displacement.

2.2.1.2 Methods

6.2.1.2.1 Study Design

Twelve healthy participants (aged between 20 and 65 years, female 4 and male 8) were recruited from Middlesex University, to conduct an experiment that involved interacting with a real painting using a haptic device. Participants were equally divided into two groups (6 participants per group).

The experiment consisted of participants exploring a painting through haptic feedback with/without sonic interaction while performing movements with the haptic device in three dimensions (Fig. 6.3) and are described as follows:

Each group explored the 'ball painting' and was involved in two different phases:

- Phase A, consisted of a subject exploring the 'ball painting' with haptic feedback while grasping the Novint Falcon robot.
- Phase B, the participants explored the 'ball painting' using haptic and sonic interactions while grasping the Novint Falcon robot.

The order of the two phases has been randomised for each group (Group 1: AB; Group 2: BA) to see whether there were any differences or not in preference vs. expectancy related to the order of the phases

At the end of the experiment, participants were asked to fill a questionnaire survey rating the experience. Each participant's interactions were recorded by three different camcorders. To avoid the bias all coders watched and discussed the videos together. Analysis coding scheme consists of labels (analytical skills, imagination, promotes spatial skills realisation and enhances touch/hearing sensory channels). Please refer to Appendix B1.

The sample size was determined by conducting an informal experiment with the same setup to estimate the difference of time spent and interaction (total time taken when participants hit the ball object) between two phases.

It was found appropriate a sample size of 10 participants to minimise the probability of type I error (false positive rate set to 0.05) and type II error (false negative rate set to 0.2) to satisfy the power of 0.8.

6.2.1.2.2 Procedure

The study was subject to Middlesex University's ethical regulations and an information package was provided to each participant before being admitted to the study. Participants were individually briefed at the beginning of the experiment following informed signed consent. Before interacting with the system, each participant was informed that he/she would be exploring an interactive painting using a haptic device for as long as they wanted to. Participants were instructed that they would explore the interactive painting twice and that the experiment would end once they completed a questionnaire.

6.2.1.2.3 Outcome Measures and Data Collection

Both qualitative and quantitative data were collected.

Participants were assessed through an 8-item questionnaire using the methodology suggested by O'Brian & Toms (2008) which evaluated some specific aspects of user experience and engagement:

1. I would be more likely to visit exhibitions where the interactive paintings are available
2. This installation made the art more enjoyable
3. It was easier to navigate through the painting without sound
4. I found the device was easy to use while interacting with the painting
5. I'd like a chance to explore the interactive painting again
6. Touch + Sound together made the experience more interactive and engaging than just Touch itself.
7. I noticed more about the painting using this device than I would without it

8. When touching the ball from the right hand side, I could hear the sound in my left ear

The questionnaires resulted in a 3-item factor (1, 5, 8) for Endurability (the likelihood of remembering an experience and willingness to repeat it), a 2-item factor (2, 4) for Usability (the ease of use and learnability of a human-made object) and a 3-item factor (3, 6, 7) for Focused Attention (attention to the exclusion of other things). The participants' responses were collected based on a 7-point Likert-type scale, which required participants to rate their level of (dis)satisfaction. In the second part of the questionnaire, four questions based on checklist items and open/closed structures were used to collect participants' opinion and previous experience.

In addition, audio-visual data (from user's interaction with the painting) was collected using three camcorders, while kinematic data (positions, velocities) recorded using the robot (Novint Falcon).

6.2.1.2.4 Results

Fig. 6.6 illustrates both the central tendency and variability of the three scale factors (mean scores) when compared with Phase A (haptics only) and Phase B (haptics + sound).

The mean scores assessing the Endurability factor (1) and Focused Attention (2) indicate no significant differences between the two groups, while group 2 seem to rate higher the Usability factor (3), i.e. participants seem to find exploring the painting with touch + sound easier than just with touch. Paired t-tests confirm that statistically no significant change occurs in scale-factor (1, 2) ($p=1$, $p=0.93$) and although scale-factor (3) show higher rate for group two rate (4.4 for group 2 and 3.5 for group 1) the p value was 0.076. Thus, suggesting that the order of the phases did not have a major impact on participants' experience and engagement with the interactive painting.
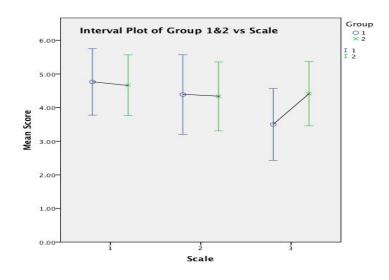
Figure 6.6: Comparison of the mean scores for each of the three scale factors measured between group 1 and 2 for Experiment 1.

Table II: Paired t-test results on the scale factors of group 1 and 2 in experiment 1

Scale Factor	Group 1 (AB)	Group 2 (BA)	Paired t-test (95% CI)
Endurability	4.76	4.76	p = 1
	SD =	SD =	CI : (-1.07,
1	1.9	1.82	1.07)
	Diff = 0		t = 0
Focused	4.39	4.33	p = 0.93
	SD =	SD =	CI : (-1.19,
Attention	2.38	2.06	1.3)
2	Diff = 0.06		t = 0.094
Usability	3.5	4.4	p = 0.076
	SD =	SD = 1.5	CI : (-1.95,
3	1.68		0.11)
	Diff = -0.9		t = -1.96

Note. N = 17 for scale factor 1 (missing data), N = 18 for factor 2 and N = 12 for factor 3.
SD: standard deviation, CI: mean confidence limits (lower, upper)
Diff: Difference between means

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In order to assess the value of the interaction, the total time spent on each of the phases per group as recorded by the system was plotted (Figure 6.7). Because the groups are not homogeneous in that no attempt is made to match them, only the relative data is useful for analysis. Fig. 6.7 shows no significant difference between phases for group 1 but a longer time for Phase B (touch + sound) with group 2, which could be associated to the phase order (i.e. group 2 experienced touch + sound first). The questionnaire results show that participants were on average willing to spend more time (102.5 sec) exploring the painting during phase B. The questionnaire results indicate that participants were actually willing to spend more time at the task than actually spent (as recorded by the system and shown in Figure 6.7).

Question 1: How many times during the previous year have you visited an art gallery/ museum?

- It appears participants were not regular gallery visitors.
    - None: N= 5 (41.7%)
    - 1-5: N = 5 (41.7%)
    - 5-10: N = 1 (8.3%)
    - More than 10: N = 1 (8.3%)

Question 2: How many different sounds could you identify while interacting with the painting?

- None of the participants managed to identify more than 5 sounds (there were 10).

Question3: How long do you think you could explore the painting before it would become boring?

- Participants were willing to spend more time (average) on touch + sound
    - Touch: 74.58 sec
    - Touch + Sound: 102.5 sec

To assess the effects of the interaction on participants' movements, a further analysis was made comparing the number of times participants touched the 'ball' (Figure 6.8) and comparing the mean movement velocities (Figure 6.9) for each group and phase. Fig. 6.8 indicates that the mean of total hits (i.e. number of times participants touched ball) is higher during phase B (touch + sound) for both groups. Interestingly, while group 1 show significantly higher velocities during phase B (Fig. 6.9), group 2 shows higher velocities during phase A, albeit of equivalent velocity magnitude as observed in group 1 during phase B
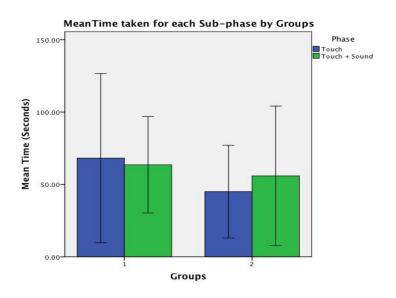
Figure 6.7: Chart of the mean total time spent exploring the ball painting in experiment 1 for each phase in both groups.
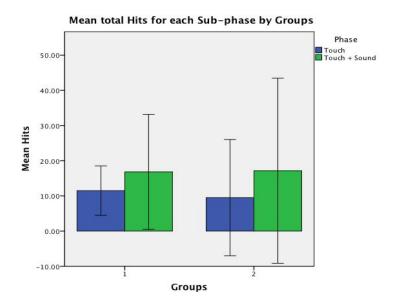
Figure 6.8: Chart of mean total hits for each phase in both groups.
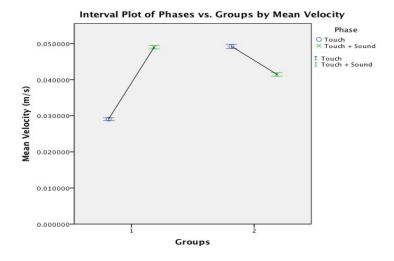
Figure 6.9: Comparison of the mean velocities during experiment 1 for each group by phase

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6.2.1.2.5 Discussions

What appears to come out from the results is that there are no major differences in terms of engagement – all participants were engaged to participate the experience.

It emerges that haptic with sonic interaction was preferred over just haptic interaction. The kinematic data results presented on the previous section together with observation analysis on the audio-visual recordings reveal some potential benefits to our approach.

While participants interacted in pairs, velocities were higher thus implying more movements were made, however further video analysis revealed not only interesting ways participants communicate, but also specific patterns started to emerge suggesting in some cases that the technology completely surpasses the work of art (painting) as participants focus their attention on the device rather than the painting. Although it was apparent that some participants moved their attention away from the painting and started exploring it using their imagination via haptic and sonic interactions, one possible explanation for some of the increased attention on the device, is perhaps in part due to the fact that participants could see the device exposed through the top of the plinth. To keep the attention focused on the painting for future experiments, it would be advisable to make the haptic device as unobtrusive as possible.

The interactive painting appears to promote spatial skills realisation. When participants were presented with the 2D image (static painting), they explored the painting using haptic-sonic cues as a 3D space. We could observe participants mapping the 2D reference with the haptic device, by exploring the boundaries first. Doing so, participants seem to create a 3D environment in their mind matching the virtual haptic environment by mapping the left and right borders of the painting with the left and right boundaries of the haptic workspace. Participants first map the virtual height and depth of the painting with the physical boundaries of the haptic

workspace and then explore the space between these boundaries. We noticed different levels of aptitude to this skill. Some explore freely, some for example get stuck at the bottom of the painting/under the ball.

6.2.2 Experiment 2

2.2.2.1 Material

6.2.2.1.1 Experimental setup
Similar to experiment 1, the only difference was the painting used in this experiment was a seaside-landscape (water painting).

The sound effects

The sound effects used in this experiment were completely different from experiment 1, all sounds were related to seaside scenery (e.g., seagull, water splashing, wind, etc.). There were totally 7 different sound effects.

6.2.2.1.2 Water viscosity algorithm
A virtual water environment was modelled using a velocity dependent spring-damper combination to simulate increased viscosity when the device's end-effector position moved under the water surface. As the movement velocity increased under the virtual water surface, the perceived effect was increased movement resistant. The algorithm uses Newton's second law to generate force feedback effects (mass-damper, spring-mass-damper and mass-acceleration) where a 0.6 maximum device damping was chosen to closely match the feeling of moving the hand under water. Table II summarises the algorithm used, adapted from the CHAI 3D library.

Table III: Algorithm - water viscosity for experiment 2

BEGIN
if position of end-effector < water level **then**
Get max damping of haptic device
Kv = 0.6 * max damping of haptic device
Get device velocity vector
Compute a scale factor [0,1] of percentage of tool volume immersed in the water

```
Scalar = -Kv * scale
Compute force damping by multiplying velocity vector by Scalar
Force -> haptic device
```
end if

2.2.2.2   Methods

6.2.2.2.1   Study Design

Twenty-four healthy participants (aged between 18 and 54 years, female 7 and male 17) were recruited from Middlesex University, to conduct an experiment that involved interacting with a real painting using a haptic device. Participants were equally divided into two groups (12 participants per group) exploring the 'water painting' using haptic and sonic interactions while grasping the Novint Falcon robot. Participants worked either alone or in pairs to interact with one painting using one Novint Falcon robot and were grouped as follows:

   • Group 1, group of individuals, participants interacted with the 'water painting' on their own.

   • Group 2, group of pairs, participants interacted with 'water painting' while cooperating with another study participant. Cooperation here refers to the two participants interacting with the painting together where they engaged in conversation and took turns to explore.

At the end of the experiment, participants were asked to fill a questionnaire survey rating the experience. Each participant's interactions were recorded by three different camcorders.

An informal experiment with the same setup was conducted to estimate the difference of time spent and interaction (total time taken when participants hit the ball object) between two groups. In order to minimise the probability of type I error (false positive rate set to 0.05) and type II error (false negative rate set to 0.2) to satisfy the power of 0.8, the appropriate sample size calculated was 20.

6.2.2.2.2 Procedure

The study was subject to Middlesex University's ethical regulations and an information package was provided to each participant before being admitted to the study. Participants were individually briefed at the beginning of the experiment following informed signed consent. Before interacting with the system, each participant was informed that he/she would be exploring an interactive painting using a haptic device for as long as they wanted to. Participants were instructed to either interact with the painting on their own and with another participant. Following the instructions, participants were left alone to explore the painting and asked, once finished, to bring the completed questionnaire to the experimenter.

6.2.2.2.3 Outcome Measures and Data Collection

Both qualitative and quantitative data were collected.

Participants were assessed through an 8-item questionnaire using the methodology suggested by O'Brian & Toms (2008) which evaluated some specific aspects of user experience and engagement:

1. I would be more likely to visit exhibitions where the interactive paintings are available
2. This installation made the art more enjoyable
3. It was easier to navigate through the painting without sound
4. I found the device was easy to use while interacting with the painting
5. I'd like a chance to explore the interactive painting again
6. Exploring the interactive painting with the other participant made the experience more enjoyable
7. I noticed more about the painting using this device than I would without it
8. When touching the water from the right hand side, I could hear the sound in my right ear

The questionnaires resulted in a 3-item factor (1, 5, 8) for Endurability (the likelihood of remembering an experience and willingness to repeat it), a 2-item factor (2, 4) for Usability (the ease of use and learnability of a human-made object) and a 3-item factor (3, 6, 7) for Focused Attention (attention to the exclusion of other things). The participants' responses were collected based on a 7-point Likert-type scale, which required participants to rate their level of sat-dissatisfaction. In the second part of the questionnaire, four questions based on checklist items and open/closed structures were used to collect participants' opinion and previous experience.

Results

Figure 6.10 illustrates both the central tendency and variability of the three scale factors when compared with the two groups (individuals and pairs).

The results are identical to those obtained with experiment 1, with main difference being the mean scores assessing Focused Attention (2) indicating in contrast higher scores during paired user interaction (group 2). However, paired t-tests confirm that statistically no significant change occurs in all three scale-factors (p=1, p=0.158, and p=0.185). The questionnaire responses revealed that participants were willing to spend more time exploring the water painting in a group (alone 255.6 sec, in a group 436.8 sec). In contrast, the total time recorded by the system show higher times spent exploring the painting than what participants were willing to spend, but no significant differences were found in between groups as recorded by the system (alone 455 sec, in a group 451 sec). However, while assessing the effects of the interaction on participants' movements by comparing the number of times participants touched the 'water' (Figure 6.11) and comparing the mean movement velocities (Figure 6.12) for each group, it is apparent that participants performed more movements while interacting in pairs.

Question 1: How many times during the previous year have you visited an art gallery/ museum?

- It appears participants were not regular gallery visitors.
    - None: N= 12 (50%)
    - 1-5: N = 6 (25%)
    - 5-10: N = 3 (12.5%)
    - More than 10: N = 3 (12.5%)

Question 2: How many different sounds could you identify while interacting with the painting?

- Only 8.33% of participants managed to identify more than 6 sounds. (There were 7).

Question3: How long do you think you could explore the painting before it would become boring?

- Participants were willing to spend much more time (average) in a pair
    - Individuals: 255.6 sec
    - Pairs: 436.8 sec
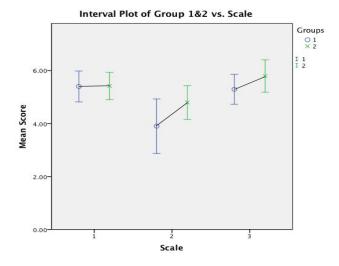
Figure 6.10: Comparison of the mean scores for each of the three ... nd 2 for Experiment 2.

Mean total Hits by Groups

Mean total Hits by Groups

umber of times
ent 2.

Error Bars: 95% CI
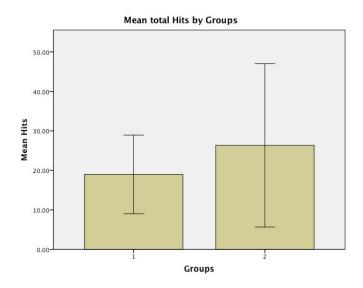
Interval Plot of Mean Velocity of Group 1&2
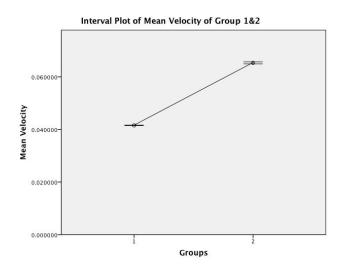
Figure 6.12: Comparison of the mean velocities during experiment 2 by each group.

6.2.2.2.4   Discussions

It appears that this form of interaction might help developing analytical skills. The best performing subject, while interacting with the water

painting on his own, was searching for more detail in the painting and explored carefully. This behaviour was consistent with the other participants. Where we can observe some participants looking cautiously at the painting and trying to match the visual detail with the haptic and sonic cues. The participants challenge the limitations and boundaries of the haptic-sonic cues in relation to the static visual (painting).

Imagination development seems to be linked to some emotional attachment. One participant expressed in a great detail her emotional attachment to the sounds and painting, referring to a childhood experience. The more she became engrossed in her own world, the more she stopped looking at the painting and was interacting with the haptic device and the sounds. We also observed that when the participants finished with the analytical part and therefore detach their attention from the painting, their next exploration stage focused on the haptic-sonic cues. It appeared that participants used more imagination, i.e. creating their own visual/virtual environment. Interestingly, we found that participants moved between varying degrees back and forth analytical and imagination exploration.

One solid observation from this pilot study, is that sound clearly enhances the haptic experience. When participants felt, for example, their hand going into the water, they experienced haptic feedback with direct correlation to the sound (splashing). The sound is also directional, for example, move hand to the left, splash sound to the left. The subject notices as the hand movements get faster, the haptic cues increasing, and so does the intensity of the splash sound. This relates to several different elements of the paintings.

Participants increase activity when the haptic and sonic cues match the virtual 3D environment with the 2D painting.

With the painting in experiment 1 (ball painting), participants were more cautious than those in experiment 2, but perhaps this is due to experiment 1 promoting shape determination and experiment 2 a more explorative behaviour. Group interactions were engaging, and participants made more

movements, which were in nature ballistic (experiment 2). Participants seemed to enjoy the collaborative exploration, engaged in communication, and shared and negotiated exploration strategies.

The results from the questionnaire in experiment 2 have also shown that participants wanted to spend much more time when doing the task as pairs (alone 255.6 sec vs pair 436.8 sec), and recorded robot data has shown that they also made more interactions (more hits and faster movements) as pairs rather than doing individually. However, the recorded data has shown that the differences in time spent between pairs and individuals were not statistically significant. Hence this did not prove Hypothesis 1.

6.3 Investigation on how group interaction with haptic and audio feedback affects children with autism

The purpose of this study is to investigate further the potential use of sound and haptic painting as a playful tool for neurorehabilitation which can be beneficial for people with neurological impairments or particularly in this study: children with autism.

6.3.1 Material

3.3.1.1 Experimental setup
The experimental setup (Figure 6.13 and 6.14) for this study has been upgraded to enhance user's experience by producing 3D binaural sound instead of stereo sound as implemented with the previous version. The

system included more speakers than the old setup (twelves vs. two) and two additional subwoofers to improve sound effects. The 3-DOF Novint Falcon robot has been replaced by a 6-DOF Phantom Omni to replicate the shape of a paintbrush which also makes more sense since the experiment was about exploring a painting. Two computers were used in this experiment: a PC running Windows 7, which ran our haptic application to generate and control haptic effects and a Macintosh computer (Mac OSX) running the 3D-Audioscape sound software (using Max/MSP environment) designed particularly for this setup to manipulate and produce 3D sounds. The two computers communicated to each other via a local network while the two software modules exchanged data via OSC (Open Sound Controller) messages.

The painting represented a seaside-landscape commissioned to a professional artist for the project. The environment was a dark room with light projected onto the painting and the device (Figure 6.14). The computer and researchers were hidden from user's view. The robot was placed on the top of a plinth for the user to grab its end- effector (paintbrush shape) and move freely (limited by the mechanical workspace of the robot - approximately 13.44 x 10-4 m3).

Figure 6.13: User interacting with the painting.

3.3.1.2 The sound effects

The 3D sounds were modelled to be dependent on the position and velocity of the haptic device. This included:

- An 'under the water' soundscape, where the participants could hear the sound of bubbles as they moved below the water surface (all other sounds were off). The feeling of moving through more bubbles increased and the velocity of the movements increased.
- An 'just above the surface' soundscape, where participants could ~~~~~~ e feeling of moving through ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~ peed of the movements, i.e. ~~~~~~~~~~~~~~~~~~~~~~~~~~ ind. ~~~~~~~~~~~~~~~~~~~~~~~~~~ ticipants reached to upper ~~~~~~~~~~~~~~~~~~~~~~~~~~ wind sounds would reduce
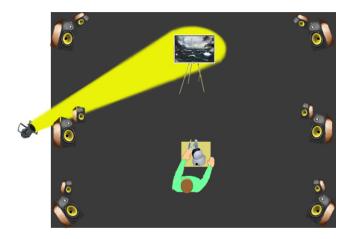
Figure 6.14: Interactive painting experimental system. Participants interact with the painting by grabbing and moving the Phantom Omni's paintbrush-shape handle.

3.3.1.3 Water bouncing algorithm

In order to match the changing movement-dependent sound, the haptic feedback algorithm has also been modified to optimize the user's

experience. The decision came due to the users' feedback from our previous study suggested it would be beneficial to feel more different kinds of force feedback (e.g. participants want to feel the waves when touching them). This was implemented using the CHAI 3D library and modelling the water using a spring-damper combination. However, in this second implementation, instead of simulating the water's viscosity, the algorithm modified to create a water bouncing effect, i.e. user's hand would be pushed in the opposite orientation of the force applied on the water. To be more specific, a force membrane has been created by a two-dimension array of nodes linked together by simulated virtual springs and dampers. The pseudo code in Table III summarises the algorithm used in this experimental setup.

Table IV: Algorithm - water's bouncing effect

```
    BEGIN

//Set values for nodes
stiffness = 40; nodeRadius = 1.3; dampingPosition = 0.4; dampingRotation
= 0.1; nodeMass = 0.006  //(kg)
create nodes[10][10]
//Get end-effector's position, radius
devicePos = getDevicePos()
deviceRadius = getDeviceRadius()
//Compute reaction forces
for  y=0 to 10
    for x=0 to 10
        //Get position of nodes[x][y]
          nodePos = nodes[x][y]->getPos()
        //Calculate force
           force = calculate(devicePos, deviceRadius, nodePos, nodeRadius,
                                stiffness)

         //Get opposite force applied on the water by negating the result
        oppositeForce = negate(force)
        nodes[x][y]->setExternalForce(oppositeForce)
    end for
end for
```

6.3.2 Methods

3.3.2.1 Study Design

Seven autistic pupils (all male, aged 7 y/o ± 14 months) diagnosed with severe general learning disabilities have been recruited from Watergate and Riverside schools. The experiment was setup as an art experience in a gallery and seven pupils were the maximum participants we could recruit at that time. The children participating in the study showed similar severe impairment in their functioning relating to basic awareness and understanding of themselves, including the people and world around them. Participants were accompanied by their teachers/minders, which sat on the background away from the children while the children interacted with a painting through a haptic device. The teachers were not allowed to communicate with the children while the experiment took place. Prior to start of the experiment, the experimenter demonstrated how to use the device and allowed the participants to familiarize themselves with the device. The study consisted of seven single case studies and comprised two phases:

- Phase 1: Participants were given instructions and demonstration on how to use the device from the researcher and then explored the painting on their own. Only one teacher/minder was allowed to remain in the same room with the participant. Verbal communication between the teacher/minder and the participant was minimized upon painting exploration to avoid any interference leading to any specific guided interaction during the experiment.
- Phase 2: Participants interacted with the haptic painting a second time, but in pairs (or in a group of three), while cooperating with another participant(s).

Participants were allowed to interact with the painting for up to 10 minutes during each phase. Due to the number of participants, it was not possible to have three pairs, hence the decision was made to include two pairs and a group of three participants in phase 2 and treat the analysis as single case

studies to see if a larger group would result in different interactions. The design of this study has been simplified to avoid any likelihood of discomfort due to the vulnerability of this particular subject group. As a result, there was no questionnaire or randomization in-group order as we did before in our previous study with healthy participants. At all times, each participant's interactions were recorded by three different camcorders. To avoid the bias all coders watched and discussed the videos together. Analysis coding scheme consists of labels (analytical skills, imagination, promotes spatial skills realisation and enhances touch/hearing sensory channels). Please refer to Appendix B2.

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All participants were provided written informed consent and this study was approved by Middlesex University research ethics committee on January 18th, 2014.

3.3.2.2 Procedure
The study was subject to Middlesex University's ethical regulations and an information package was provided to each participant's parents. Participants were admitted to the study following informed signed consent. Participants' teachers/minders were briefed at the beginning of the experiment. Before interacting with the system, each participant was informed that they would be exploring an interactive painting using a haptic device for as long as they wanted to. Once they finished, they were instructed to go to another room and waited until the next phase of the experiment, when they interacted with the painting again in a pair (or group of three) with another participant(s).

3.3.2.3 Outcome Measures and Data Collection
Audio-visual data (from user's interaction with the painting) was collected using three camcorders, while kinematic data (positions, velocities) recorded using the robot (Phantom Omni).

3.3.2.4 Results

The results (correlated with the videos) show that participants' movements are varied, and some participants seem to be more explorative than the others (subject 1, 6&7). It also implies that when participants play together in a pair or a group, they have a tendency to move differently from doing it alone (e.g. the z coordinates of subject 2's movements were most of the time greater than 0 pointing out that he preferred to move over the water surface however when exploring it again with subject 1, he became more explorative thus his movements were more diverse).

To assess further the interaction effects as a whole on participants' movements, three different analyses were carried out. The results seem to indicate that participants moved faster alone although there is no significant difference between interaction types (alone approximately 0.15 m/s, in a group approximately 0.14 m/s – figure 6.15). In contrast, Figure 6.16 and Figure 6.17 show that the mean total time spent and total hits (the number of times participants touched the water) in groups are higher than individuals. As a whole, it appears that participants made more movements and spent longer times interacting with the painting while playing in groups. A closer inspection (Table IV and V) looking at the individual contributions for the participants in the pairs and in the group suggests that participants spent less time (individually) exploring the painting ($p = 0.06$ and $P = 0.19$) and touched the surface of the water also less than on their own ($p = 0.46$ and $p = 0.27$).
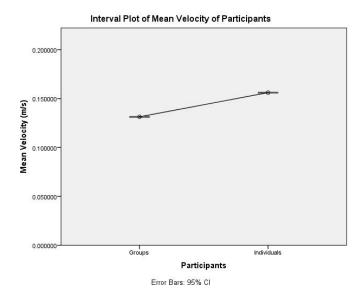
Interval Plot of Mean Velocity of Participants

Interval Plot of Mean Velocity of Participants

als (participants
roups (worked in pairs

Error Bars: 95% CI

Mean Time Taken by Participants

Error Bars: 95% CI

t exploring the

Mean Total Hits by Participants

Mean Total Hits by Participants

Error Bars: 95% CI
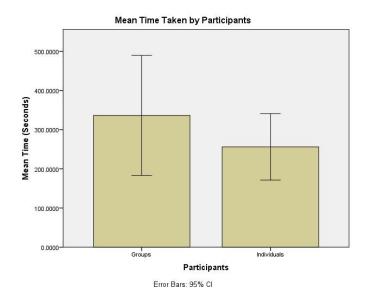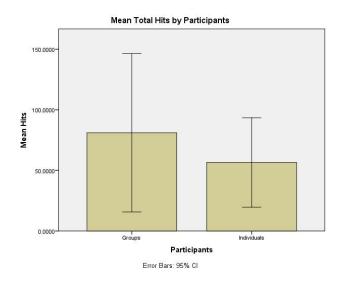
Figure 6.17: Charts of the mean total hits: number of times participants touched the water.

Table IV: One-way ANOVA results on the hits and time spent of individuals and group

Factor	Group	Individuals	ANOVA (95% CI)
Hits	81 SD = 26.28	56.57 SD = 39.83	p = 0.36 F = 0.91
	Diff = 24.3		
Time Spent	336.19 SD = 61.67	263.65 SD = 89.83	p = 0.24 F = 1.57
	Diff = 78.81		

SD: standard deviation, CI: Confidence Interval, Diff: Difference between means.

3.3.2.5 Discussion

The results show the overall engagement of all participants regardless how and who they interact with. They seemed to be happy and to have enjoyed the experience. The analysis of the kinematic data with audio-visual data revealed an interesting fact: children interacted with the painting differently depending on their imagination and which sound they preferred. For instance, participant 2 spent almost all of his time moving over the water because he seemed to like the water splash and windy sound while participant 3 on the other hand, liked the underwater sound. It also appears that some children might develop their analytical skills through this kind of interaction. As mentioned before, some participants seemed to be more explorative than the others, they moved in various ways to explore different sound and haptic feedback. This finding might indicate that adding more sound and haptic feedback could result in longer exploration and engagement with the installation.

The 3D sound effect also had a strong impact on user's reaction. Participant 7 was looking and then running around the room to find out where the sound came from. It is interesting to see how the sound effect contributed to the way the children interacted with the artefact. In fact, humans in general, have the tendency to use their imagination while interacting with good sound effects. In contrast, one participant in our study used the device while making circular motions and one can assume this related to imagining stirring (mixing) the sea because he could actually hear the sound corresponding to his action.

The way participants communicated to each other while interacting in pairs or group is also worth mentioning. On conversation with their teachers following experiment completion, we have learnt that this cohort of autistic children always has difficulty to talk to each other. Nevertheless, in this particular experiment, when participants explored in a group (or pairs), they had to 'negotiate' with each other and take turns to use the device.

It rises the opportunity to apply this type of interaction for social skills development which is important in human cognitive development especially for children with autism. However, the fact that took a while before participants in the group of three to engage as a group only reinforces the notion of the difficulties autistic children face when the number of people they have to interact with increases. But it is also encouraging to observe, that perhaps because of the curiosity that the interactive painting generated, the individual bursts of wondering around slowly resulted in coming together and converged towards participants starting to do things together.

The results have shown that the mean total time spent and total hits in groups are higher than in individuals. However, there was no statistically significant difference; hence similar to experiment 2 from section 6.2.2, this did not prove Hypothesis 1.

6.4 Chapter summary

This chapter presents and analyses the results of three different pilot studies. The results can be summarised as follows:

Participants working in a group would reshape the individuals' mental model formed from the previous activity, and group interaction task was engaging (based on the observation from captured videos and interviews afterward) for the participants, thus encouraging them to make as many movements as possible (approximately 3,500 movements in 10 minutes). Group interactions showed some positive interactions and communications between participants. This trend was consistent for both healthy and neurological impairment people (autistic children), thus the experiment introduced later in chapter 7 expanded this further by focusing only on group interaction (and ignoring individual interaction) but comparing two different conditions (real vs virtual environments, section 7.3). Chapter 7 takes this further by investigating if it is possible to transfer a real-life collaborative task to a virtual domain using haptic technology.

This chapter also showed that the developed framework satisfied the following benchmarks: scalability - the framework worked well in different environments as it was implemented in both laboratory and art gallery environments; imitation – based on participants' feedback, haptic feedback reflected their expectation and gave them the feeling that they were touching the real objects; and social success – as mention above, participants were engaged when doing the task and they did talk to each other.

The safety benchmark has not been considered since the haptic robots employed for the tasks are commercial devices (Novint Falcon, Phantom Omni) that are already very safe to interact with.

Chapter 7: Further study: User's behaviours while working in a group – real vs. virtual environments

Chapter 6 has suggested that participants may prefer group interaction and may be more willing to work with someone than on their own on those particular tasks. The main aim of chapter 7 is to investigate how different environments (real vs. virtual) and communication modalities (with vs. without talking to each other) affect the quality of interactions between humans. The results suggest that doing the task in the virtual world was more difficult and required more effort to complete than doing it in the real world even though virtual world task was more engaging. The strategies applied by users to finish the task in each world were also different. The results from this study will probably help to develop a model to predict user's behaviours in a collaborative task which could be potentially used for remote interaction between users via haptic interfaces.

Due to the fact that haptic-based rehabilitation system always require extremely low latency (the update rate is at least 1KHz) to retain any fidelity (Fenghua et al., 2011), it is almost impossible to implement such system remotely in real time (two or more users sharing a same virtual environment with haptic feedback via the Internet) with the existing technology. There is one possibility to tackle this issue that is to develop a solution which could predict user's behaviours so that rendering force feedback correspondingly (and locally thus eliminating the latency caused by data transfer). Nevertheless, this solution is difficult to achieve because there is very little research has systematically investigated how two agents would interact to complete a task in the virtual world with the addition of haptic feedback. This thesis evaluates the performances of healthy people working in pairs to fulfill a collaborative task in both real and virtual environments. A pilot study is presented in the following section of this chapter. The main aim of this study is to investigate how different environments (real vs. virtual) and communication modalities (with vs. without talking to each other) affect the quality of interactions between humans.

7.1 Material

7.1.1 Sensor calibrations

There were four Force Sensing Resistors (FSR) attached to four sides of a plastic cube to measure the interacting forces. The FSR is a polymer thick film (nominal thickness: 0.46 mm) device. It has a high resistance (1 MΩ) which decreases with an increase in the force applied to the active surface. It consists of a flexible substrate with printed semi-conductor, a spacer and a flexible substrate containing printed interdigitating electrodes (figure 7.1).
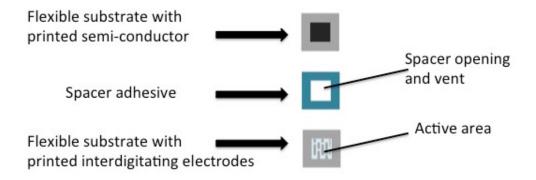
Figure 7.1: FSR Construction

FSRs have similar properties to strain gauges, load cells or pressure transducers. However, they are less precise and less repeatable. Force accuracy ranges from approximately ± 5% to ± 25% depending on the measurement and actuation system, whereas the force resolution is better than ± 0.5% of the full usable force.

Although this type of sensor has poor accuracy, it would be usable as force input after applying curve fitting calibration method. The single sensor's output voltage was recorded based on pre-measured force points using a calibrated force gauge. The means and standard errors of the selected force points taken from the eight single sensor assemblies (four for each cube) over five repetitions are plotted (figure 7.2).
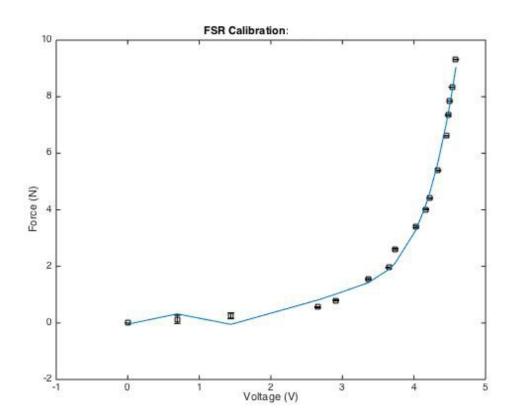
Figure 7.2: Curve fitting calibration method for FSR assembly

The resultant equation with the force coefficients is as follow:

Force = -1.042 x V^5 - 1.057 x V^4 + 3.865 x V^3 – 5.766 x V^2 + 2.99 x V – 0.043 (7)

Where, V is the FSR output voltage obtained from the current-to-voltage converter circuit.

There were two special Augmented Reality (AR) markers attached on the top of each cube (figure 7.3). These markers could be detected and tracked (position and orientation) by an AR extension for Unity named Vuforia. Originally developed by Qualcomm, Vuforia is one of the industry leading

VR platforms. It has been chosen to conduct this study because of the high accuracy, ease of use, flexible and completely free for non-commercial purpose. The accuracy of this software has been tested out by performing a simple trial: moving the cube along a straight line (X axis) and then plotting the recorded result against a model generated by minimum jerk model first introduced by Hogan (1984) for one joint (elbow joint) and Flash & Hogan (1985) for multi-joint movements. Hogan pointed out that the movements of human arm should be smooth by minimizing the jerk. The jerk is the rate of change of acceleration with respect to time i.e. the third time derivative of the position. Minimum jerk theory states that if the parameter given by the following equation is minimized, the movement will have maximum smoothness:

$$(8)$$

Where x $$J = \int_0^d |\frac{d^3 x}{dt^3}|^2 dt$$ parameter is the position of patient's arm at the time t and d is the duration of this movement. By using minimum jerk polynomials, the velocity and acceleration of the human's movement can be controlled: polynomials can be redefined in a real time context to replace an old trajectory with the new one. This method is commonly used for a straight-line movement (Amirabdollahian, 2002). A range of parameter τ is chosen as follows:

$$-1 \leq \tau \leq 1 \qquad (9)$$

In real time application, this can be scaled to the time of movement. A polynomial with odd power is necessary for the guarantee that the acceleration of movement at the beginning and end is zero.

following 7th order polynomial:

$$p = a + b\tau + c\tau^2 + d\tau^3 + e\tau^4 + f\tau^5 + g\tau^6 + h\tau^7$$

This equation's derivatives respect to the parameter τ applied in the beginning and end of the movement

- For start and end positions:

$$p|_{\tau=-1} = P_{start} \qquad p|_{\tau=1} = P_{end}$$

- Velocity is zero at start and end:

$$p'|_{\tau=-1} = 0 \qquad p'|_{\tau=1} = 0$$

- Acceleration is zero at start and end:

$$p''|_{\tau=-1} = 0 \qquad p''|_{\tau=1} = 0$$

After applying above assumptions, the polynomial b

$$p = a + b\tau + d\tau^3 + f\tau^5 + h\tau^7$$

And all of its coefficients can be identified as:

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$$a = \frac{(p_{start} + p_{end})}{2}$$

$$p'|_{\tau=0} = v_{mid} = b$$

$$d = \frac{35}{16}\Delta_p - 3b$$

$$f = 3b - \frac{21}{8}\Delta_p$$

$$h = \frac{15}{16}\Delta_p - b$$

Where:

$$\Delta_p = p_{end} - p_{start}$$

The mid velocity is needed to minimize the following integral (illustrated by figure 5):

$$J_{param} = \int_{-1}^{1} |p'''|^2 d\tau \qquad (17)$$

To achieve the minimum jerk, mid velocity should be given as:

$$b = \frac{15}{16}\Delta_p \qquad (18)$$

As a result, the *h* coefficient becomes zero and therefore 7th order polynomial reduced to a 5th order polynomial.

Figure 7.4 and 7.5 show the real data vs. minimum jerk in X position and velocity (Savitzky-Golay filter applied for real data) respectively. The recorded data as showed, was very close to minimum jerk model which suggested that the tracking was reliable.

Mid Velocity Versus Jerk Parameter

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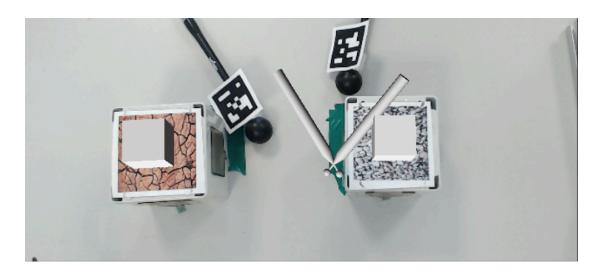
Figure 7.3: Vuforia Augmented Reality (AR) markers attached on the top of each cube.
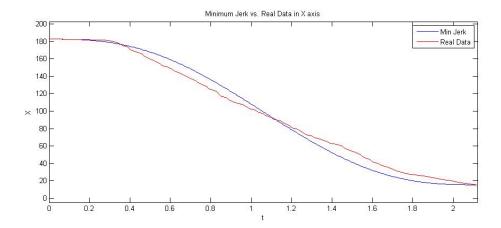
Figure 7.4: The real data vs. minimum jerk in X position
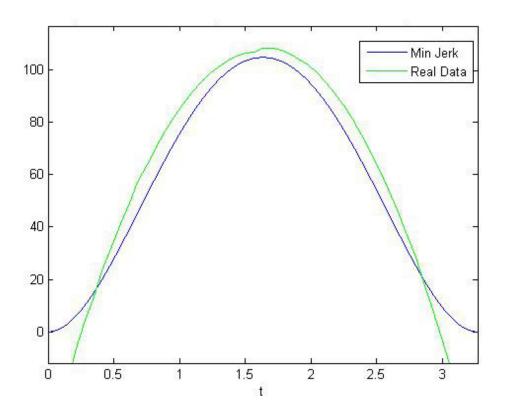
Figure 7.5: the real data vs. minimum jerk in velocity

Two other AR markers (figure 7.3) attached to the styluses (used by participants to lift the cubes up) were compatible with AR toolkit plus – an AR open source library. The reason why two separate AR platforms have been used for this study because while Vuforia was very accurate for the position tracking, much better than AR toolkit plus, it was not very good to detect smaller size trackers – any size smaller than the size used in this study would give a poor result. Since bigger size markers attached to the styluses may interfere participant's interaction, AR toolkit plus was a good solution due to its tracking ability with small size markers. In addition, it was also very accurate to calculate the angle between two markers which was the only kind of data needed from the styluses. A protractor has been used to measure the accuracy of the angle calculation from AR toolkit plus as in figure 7.6.

Figure 7.6: AR toolkit plus angle calibration

The test result (table VI) states that the calculations were highly accurate and did not have drift issue i.e. the target (virtual object) shifts away from tracking marker which causes the inconsistent estimation.

Table V: Test results on the estimation of interaction angles using AR toolkit plus

Protractor	AR toolkit plus	Duration (s)
9^0	Avg. 8.91^0	30
90^0	Avg. 89.82^0	30
110^0	Avg. 110.81^0	30
180^0	Avg. 180.77^0	30
220^0	Avg. 219.93^0	30
270^0	Avg. 269.35^0	30

The psychological aspect has been also taken into account in this study. There were two Galvanic Skin Response (GSR) sensors (e-Health sensor platform – commercial product for Arduino as in figure 7.7) attached to participants' fingertips to measure the stress level of each participant based on the electrical conductance of the skins (assuming that people will increase their stress level through sweating which changes their skin conductance).

Figure 7.7: e-Health GSR sensors for Arduino

To increase the accuracy of the measurement, the baseline of each participant has been recorded before the trial started. During this time, they have been asking to close their eyes and relax.

The virtual world was adjusted to as close as possible to the real world. All virtual objects had the same properties as their real counterparts (size, weight and friction coefficients). The friction coefficients were measured using tilted plane and force gauge.

The tilted plane method: place the cube with the FSR facing down on top of a rubber surface (similar material to the stylus's contact point) as in figure 7.8. Tilt the plane until the cube begins to slide. The static coefficient of fiction μ_s was calculated as follows: $\mu_s = tan\ \alpha$ (figure 7.9). It is due to the fact that:

$F = W \sin \alpha$ *(19)*

$N = W \cos \alpha$ (20)

$F_f = F_s$ (21)

Where:

F = Traction force

N = Normal force

W = Weight

F_f = Friction force (static fiction in this case: F_s)

If α is the angle of the plane just before the cube starts to slide, then static fiction force will reach its maximum value, so:

$F_s = \mu_s N = \mu_s W \cos \alpha$ (22)

While:

$F = F_s$, so:

$W \sin \alpha = \mu_s W \cos \alpha$ (23)

Finally:

$\mu_s = W \sin \alpha \, / \, W \cos \alpha = \tan \alpha$ (24)

In this study, α was 48.9^0 so $\mu_s = 1.16$
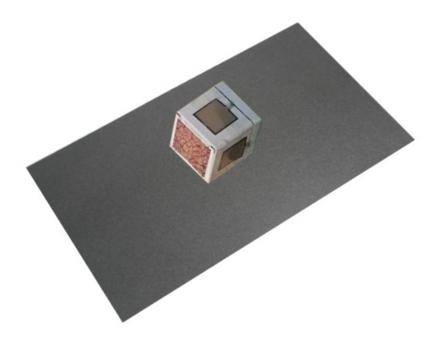
Figure 7.8: The cube with the FSR facing down on top of a rubber surface
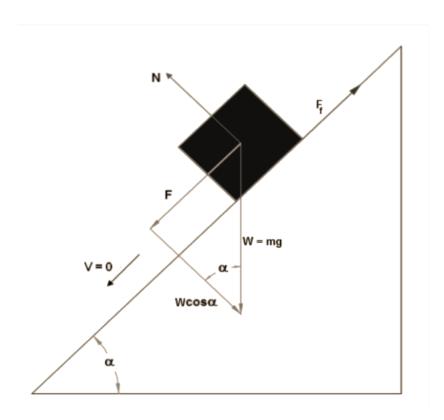
Figure 7.9: Tilted plane method to measure static friction

The dynamic coefficient of friction was measured using a force gauge (figure 7.10): kept pushing until the cube started to move at a constant velocity. The coefficient was approximately 0.5

Figure 7.10: Using a calibrated force gauge to measure dynamic friction

The point of view for each participant in the virtual world was also tailored in attempt to match the same perspective as in the real world (figure 7.11 and figure 7.12)
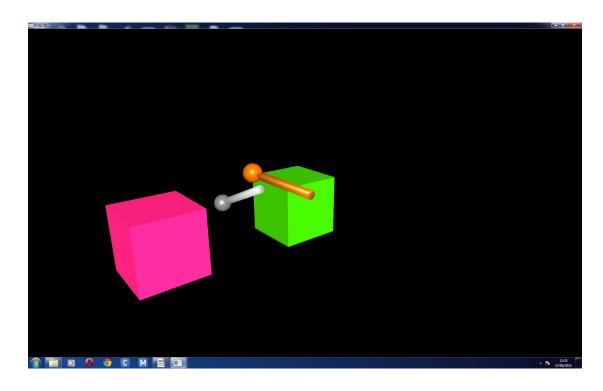
Figure 7.11: point of view for user sitting on the left hand side
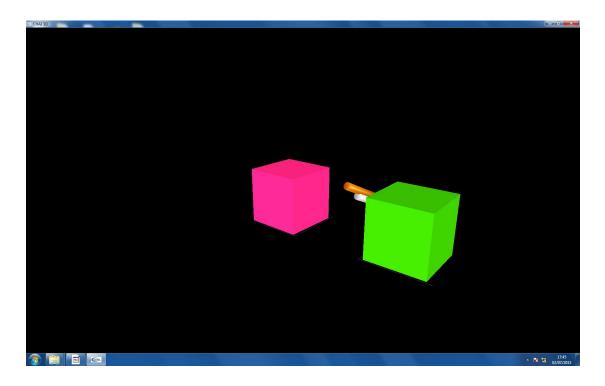
Figure 7.12: point of view for user sitting on the right hand side

7.1.2 Experimental setup

Figure 7.13 illustrates the actual system setup which consists of two PCs with two Phantom Omni devices and a laptop all connected together in a network, two cubes with eight FSR sensors (measuring contact forces), two Galvanic Skin Response (GSR) sensors (used to analyse users' stress level), and two webcams (one for Vuforia - a commercial augmented reality SDK and one for AR toolkit plus – an augmented reality open source library) for tracking the orientations and positions of the cubes and the contact points.

The force data collected from the cubes was sent via Bluetooth connection to the laptop running a synchronization software developed in Unity. The software logged also all data from the PCs, webcams and GSR saved into one file. Figure 7.14 shows two participants performing the collaborative task in the virtual environment using the haptic interfaces, while figure 7.15 illustrates the virtual cubes environment. In order to match as much as possible the tasks, in the real world, participants used the styluses (to replicate the haptic devices used with the virtual environment) to interact with the cubes (figure 7.16) and GSR sensors attached to their non-dominant hands were used to capture possible stress indicators during task execution.

Figure 7.13: Setup of the study: two cubes, two webcams, two Phantom Omni, two PC with two screens, two pairs of GSR sensors and two styluses with AR markers.

Figure 7.14: Participants doing the task in the virtual environment

Figure 7.15: Virtual environment for the cubes task
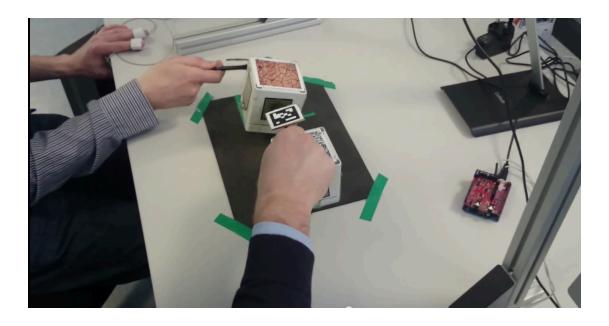
Figure 7.16: Participants doing the task in the real environment

7.2   Methods

7.2.1 Study design:

Twenty-four naïve healthy participants (mean age: 26.36, standard deviation: 5.76; gender: 8 females and 16 males) who know how to operate a computer have been recruited from Middlesex University to conduct an experiment that required their engagement with a collaborative task. Participants were divided into four equally numbered groups. They have had to work in pairs to lift cubes (both virtual and real objects) and stack them on the top of each other in an unspecified order and following a specific sequence (e.g. lift cube A on top of cube B or cube B on top of cube A). Each pair was involved in four different phases:

- Phase A: Participants manipulated the cubes together in the real world without talking to each other.

- Phase B: Participants manipulated the cubes in the real world and are encouraged to talk to each other.

- Phase C: Participants manipulated the cubes in the virtual world using the haptic device without talking to each other.

- Phase D: Participants manipulated the cubes in the virtual world using the haptic device and are encouraged to talk to each other.

The order of the four phases has been randomised for each group (Group 1: ABCD; Group 2: CDAB; Group 3: DABC; Group 4: BCDA) to see if there are any differences in relation to quality of the interaction, kinematic features and psychophysiological responses (e.g. stress/cognitive load responses extracted from galvanic skin responses) related to the order of the phases. At the end of each experiment participants have been asked to fill a questionnaire survey rating the experience. The assumption was that performing an interactive task in a virtual environment does not affect negatively the quality of movement, task engagement, motivation and skill

attention of participants when compared to do the same task in the real world. Given that haptic interfaces have been developed to facilitate safe and natural interactions via the sense of touch, it was expected that a task carried out in the virtual world with haptic feedback can match or at least provide a close approximation to the same task in the real world. It was also assumed that the communication between participants plays a crucial role in the success of the task.

The result of this study, however, does not support the initial assumption: although doing the task in the virtual world with haptic feedback can provide some level of reality, it did not come close as to do the same task in the real world. In other words, people's interactions and strategies to finish the task were different between virtual and real world. The details and analysis of this result will be presented later on in this chapter.

The sample size was determined by conducting an informal experiment with the same setup to estimate the difference in terms of applied forces, movements, and orientations of the participants between two environments (real vs. virtual). It was found an appropriate sample size of 22 participants was needed to minimise the probability of type I error (false positive rate set to 0.05) and type II error (false negative rate set to 0.2) to satisfy the power of 0.8.

All participants were provided written informed consent and this study was approved by Middlesex University research ethics committee on January 21st, 2015.

7.2.2 Procedure

The participants were informed that they would have to work together as pairs to stack cubes on top of each other for undetermined period of time and once finished; the participants were required filling in a questionnaire survey.

The participants had one minute to relax before the trial. While doing so, GSR sensors were attached to their fingertips have recorded the baseline of their skin conductance. They have been requested to keep the hand (subdominant hand) with GSR sensors steady during the trial.

They have been asked to use styluses (one stylus for each participant) with a sphere-shaped rubber top to interact with the cube in the real world. In the virtual world, they had to interact with the virtual objects using a stylus-shaped haptic device (Phantom Omni).

Once participants finished the task in one environment, they would have to switch to do the same task in other environment (virtual to real or vice versa). The task would be considered as failure if the pair dropped a cube completely.

Each pair will be assigned to one of four sequences randomized into four phases:

- Sequence 1: ABCD
- Sequence 2: CDAB
- Sequence 3: DABC
- Sequence 4: BCDA

7.2.3 Outcome measures and data collection methodology:

Participants have been assessed through a questionnaire using the Intrinsic Motivation Inventory (IMI), which has been used by Colombo et al., (2007) and Mihelj et al., (2012). It consists of twenty-three statements divided into

four scales: interest/enjoyment, perceived competence, effort/importance and pressure/tension. In addition, kinematic data (positions, forces) from the participants' interaction will be collected using a tracking application created particularly for this experiment and FSR sensors while, stress levels data are recorded using GSR sensors.

7.2.4 Results

Figure 7.17 illustrates the differences between two environments (real vs. virtual) from the questionnaire's data. The mean score indicates that a positive trend occurs from the real to virtual environment for the *Interest/Enjoyment* factor (1). Further inspection with paired t-test (table VII) shows high significant results (p<0.001), which point out that the participants enjoyed the virtual world more than the real world. In addition, 20 out of 24 participants (83.3 %) replied that their favourite phase was the virtual environment (with or without communication).

The *Perceived Competence* factor (2) is significant higher (p<0.001) in responses from real world than from virtual world, closely followed by the *Effort/Importance* factor (p = 0.001). Those results suggest that participants felt more competent and easier to fulfil the task in the real world. When asked, 17 out of 24 (70.83 %) responded that they could manipulate the cubes easily in the real world while 5 out of 24 (20.83 %) felt they could do well in both environments. There is no significant difference between two environments in the *Pressure/Tension* factor (p = 0.154).

The questionnaire's data suggests an interesting trend: participants preferred the virtual world to the real world even though it was more difficult. Some participants when interviewed, have commented "it was difficult to do it, so it was more fun to succeed" or "was harder to know what the other person was doing. Made it more challenging". Some of them felt the task in the real world "was quite boring" while doing it in the virtual

world made it "like a game" and they said "the innovation of the technology made it more interesting".

20 out of 24 participants (83.3 %) believed that communication (talking while doing the task) helped them to perform the task better. This statement is very true especially while participants performing the task in the virtual world, 11 out of 12 pairs (91.66 %) could not complete the task successfully without communication. However, this does not apply for the real world. All pairs could be able to finish the task easily with or without communication.
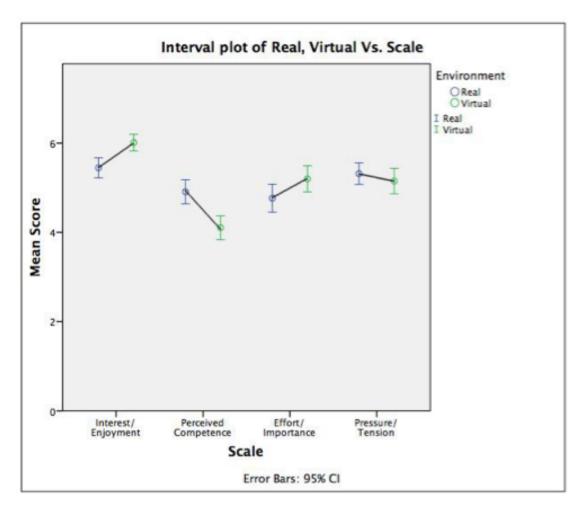
Figure 7.17: Interval plot of the differences between two environments (real vs. virtual) from the questionnaire's data
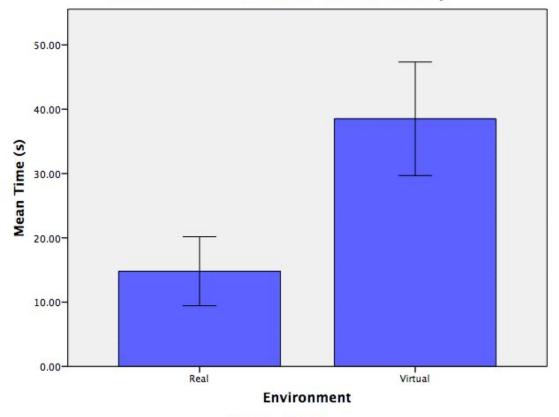
Table VI: Paired t-test results on the scale factors of virtual and real environments

Factor	Virtual	Real	Paired t-test (95% CI)
Interest/Enjoyment	6.01 SD = 1.22	5.44 SD = 1.47	p = 0.000
		Diff = 0.56	CI : (0.37, 0.76)
			t = 5.73
Perceived Competence	4.1 SD = 1.62	4.9 SD = 1.63	p = 0.000
		Diff = -0.8	CI : (-1.04, -0.56)
			t = -6.73
Effort/Importance	5.2 SD = 1.61	4.76 SD = 1.72	p = 0.001
		Diff = 0.43	CI : (0.18, 0.68)
			t = 3.41
Pressure/Tension	5.15 SD = 1.57	5.31 SD = 1.32	p = 0.154
		Diff = -0.16	CI : (-0.39, 0.06)
			t = -1.43

Note. N = 24 per scale factor. SD: standard deviation, CI: mean confidence limits (lower, upper), Diff: Difference between means.

Figure 7.18 compares the mean time taken while figure 7.19 presents the mean total force performed to finish the task successfully in both environments with communication. It is clearly indicated that participants needed more time (38.51s vs. 14.8s: approximately 2.13 times) and applied more force (2.09N vs. 1.46N) to complete the task in the virtual world. It is again supporting the above responses that the task in virtual world is much more difficult to perform.
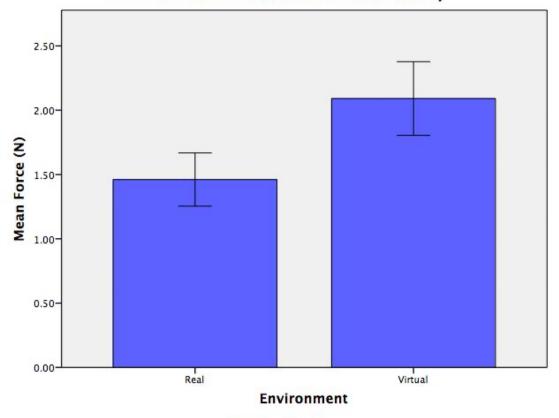
Figure 7.18: Mean time taken to finish the task in real vs. virtual environments.

Figure 7.19: Mean force applied to finish the task in real vs. virtual environments
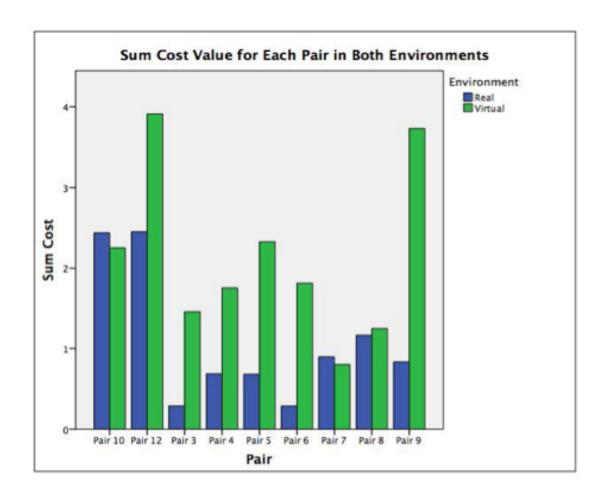
Figure 7.20: Total cost applied to finish the task in real vs. virtual environments

The total cost of both participants to finish the task was calculated using the following equation:

$$J = \sum_{t=0}^{T} \{f_1{}^2(t) + f_2{}^2(t) + 2e^2(t)\} \qquad (25)$$

Where T is the total time; f_1 and f_2 are the interaction forces applied by the participants; e is the error defined by the difference from the current position of the cube to the target position P: $e(t) = p(t) - P$; in this trial, two participants applied forces to move the same rigid object thus $e_1(t) = e_2(t) = e\ (t)$

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Figure 7.20 presents the total cost performed to finish the task successfully in both environments with communication. It can be seen that participants made more effort to complete the task in the virtual world; three pairs were excluded from the analysis due to the missing data (data loss while transfer via Bluetooth connection) and the values have been scaled down (divided by 10^5) for better presentation.

Further analysis with the kinematic data (accommodated with observations during the trial) shows how different the strategy was to fulfil the task in each environment: there was a consistent trend of how forces were applied to lift the cubes up: in the real world, both participants lifted a cube up as soon as the session started. As seen in figure 7.21, both participants applied decent forces (more than 1.5 N from most participants, close to 1 N from participants 11 and 23) immediately; while in the virtual world, they just applied very low forces (or not at all as seen from participants 11, 12, 18, 23 and 24; This might be linked with the need to locate the position of the virtual cube in the first few seconds. The reason for this behaviour can be explained as participants lost their depth (third dimension) perception while interaction in the virtual world. The discrepancy with perceiving the third dimension in a 2D screen might have contributed to the added difficulty to locate the positions of the cubes before lifting the cube up. In the real world this limitation was less of a problem and participants were able to immediately locate the cube's position and orientation quicker.

It is also worth to mention that participants had a tendency to move over the target destination in the virtual world before re-adjusting the height of the cube to the target position. Moreover, in most cases, the skin conductance collected from GSR sensors was slightly higher in the virtual world even though not very distinctive (figure 7.22). It suggested that participants might have the task in the virtual environment slightly more intensive.
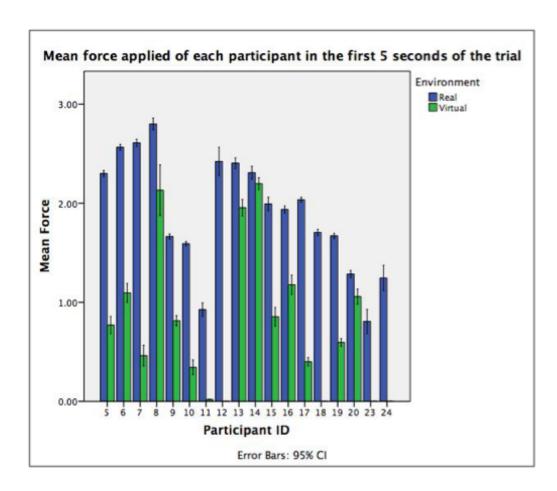
Figure 7.21: Mean force applied of each participant in the first 5 seconds of the trial.
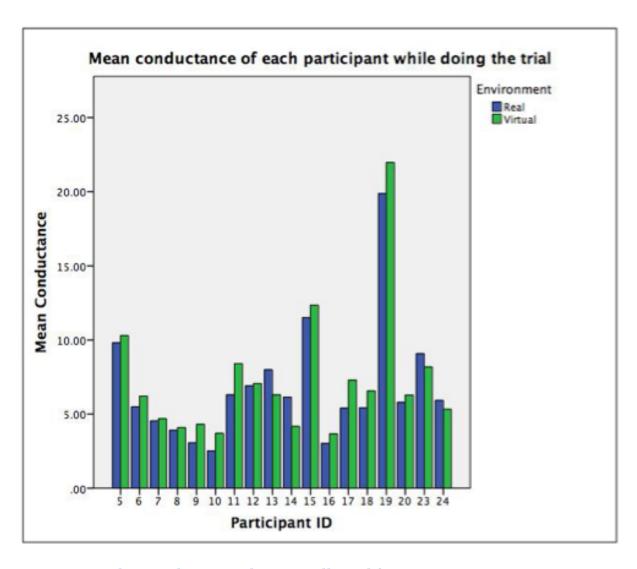
Figure 7.22: skin conductance changes collected from GSR sensors between real and virtual world of each participant

7.2.5 Discussions

The results from this chapter showed that participants were more engaged doing the collaborative task in the virtual environment using haptic devices even though it was more difficult and required them to put more effort than doing the same task in the real world. They seemed to be happy and enjoyed the experience especially in the virtual world phase with communication allowed between participants. When allowed to talk to each other, it enabled participants to compensate for their depth perception limitations by proving each other corrective instructions in order to increase the chance of finishing the task successfully in the virtual world. The depth

perception also had a substantial impact on the strategy used to fulfil the collaborative task. With reduced depth perception, participants took longer, increased their effort as well as caused them to perform more errors in the same task. Nevertheless, it did not strongly increase participants' stress levels. In some cases, participants felt less tension while doing the task in the virtual world than the real world. Perhaps, the 'fun' factor has played a crucial role in these circumstances.

The results presented in this chapter could potentially guide further work identifying important factors (aspects affecting user's performance and their strategy to complete a task in different environments) of how to simulate a real collaborative task (which could be modified in the future as a therapeutic exercise) in the virtual world with the support of haptic technology. These factors should be taken into account in order to design collaborative tasks in the future to increase the success rate as well as reducing the metabolic cost.

7.3   Chapter summary

Data collected from this chapter was used to train a predictor in chapter 8 assuming that it could help to compensate the data loss due to network failure.

Chapter 8: Modelling User's input prediction using exogenous input (NARX) and long-short term memory (LSTM) neural networks

The use of robots in a telerehabilitation paradigm could facilitate the delivery of rehabilitation on demand while reducing transportation time and cost. As a result, it helps to motivate patients to exercise frequently in a more comfortable home environment. For such paradigm to work, it is important that the robustness of the system is not compromised due to network latency, jitter, and delay of the internet. Chapter 8 proposes a solution to data loss compensation to ensure the quality of the interaction between the user and the system is maintained. Data collected from chapter 7 was used to train a robotic system to adapt to the users' behaviour. The proposed approach uses nonlinear autoregressive models with exogenous input (NARX) and long-short term memory (LSTM) neural networks to smooth out the interaction between the user and the predicted movements generated from the system. LSTM neural networks are shown to learn to act like a real human. The results from this chapter have shown that, with an appropriate training method, the artificial predictor can perform very well by allowing the predictor to complete the task within 25 seconds versus 23 seconds when performed by the human.

8.1 Material

Telerehabilitation robotics is a promising solution supporting routine care which can help to transform face-to-face and one-on-one treatment sessions that require not only intensive human resource but are also restricted to some specialised care centres to treatments that are technology-based (less human involvement) and easy to access remotely from anywhere. However, there are some limitations such as network latency, jitter, and delay of the internet that can affect negatively user experience and quality of the treatment session. Moreover, the lack of social interaction since all treatments are performed over the internet can reduce motivation of the patients. As a result, these limitations make it very difficult to deliver an efficient recovery plan (Mutingi & Mbohwa, 2015; Morreale, 2007).

Carignan et al. (2006) defined the major types of telerehabilitation interactions as: (i) unilateral: patient and therapy are examined with a time-delay; (ii) interactive bilateral: patient and therapist communicate through a virtual environment (e.g., video, virtual, and augmented reality) but without direct force-feedback in either direction; (iii) cooperative bilateral: therapist and patient communicate directly with each other, remotely but with video, force, and kinesthetics feedback.

A distributed VR-haptic based system working in a shared virtual environment could enable two or more users doing the same task in remote locations. Nevertheless, the transparency of such a system is compromised by network issues that occur during long-distance communications, such as the loss of data packets or time delays (Hirche & Buss, 2007). The effects of delayed feedback on task performance have long been investigated by psychologists since the 1960s. Kalmus et al. (1960) analysed the handwriting transmitted over a network and found that the delayed visual feedback increased completion time and errors made. A study conducted by Sheridan & Ferrell (1963) using master-slave robot arms also

pointed out that visual latency was responsible for decreasing the performance of manipulation tasks.

Initial studies regarding delayed virtual feedback in collaborative virtual environments (CVEs) showed that the impact of the delay varied according to the difficulty of the task; therefore, it is impossible to pick a particular number as a threshold for the delay (Jay, 2007; Gergle et al., 2006). For instance, Vaghi et al. (2001) performed a study of a collaborative virtual ball game where two players must hit a virtual ball into their opponent's goal. The study provided qualitative evidence that the game did not have any issue and could be played smoothly with a delay of 150ms. After this, it became harder to play and was almost impossible after 500ms. A study of a telerobotic surgery system conducted by Kim et al. (2004) showed that the performance was not affected until the delay reached over 250 ms. Besides, when the delay was around 400 ms, the operators found it more challenging to perform the task continuously.

Although the understanding of tolerable ranges of visual delay is still vague, it is evident that delayed visual feedback affects task performance in terms of increasing time taken to finish the task and error rates. A similar picture has been found with a delay in haptic feedback. However, the haptic delay tends to be more sensitive than visual latency; hence, its impact on performance is more significant. For example, a study revealed that the errors started to rise from haptic delays of 25 ms, while it only happened from visual delays of 50 ms (Jay et al., 2007).

Recent studies have focused on the compensation of harmful effects due to haptic/physical delays caused by data loss via network environments. For example, Zhang et al. (2015) introduced a torque-limiter mechanism for their telerehabilitation system: whenever the interaction torque surpasses the predefined threshold, the torque-limiter will force the device to move freely regardless of its previous positions. Meli et al. (2017) on the other hand, proposed an approach to exclude force feedback data and only used

position data for synchronisation between the client and server. The data loss then could be predicted with basic motion compensation. This approach helped to compensate data transmission delays and thus, facilitating activity completion without significant problems.

This thesis proposes a different approach to data loss compensation. It used all data collected from chapter 7, including the force feedback interaction, to train the system to adapt to user's behaviours in a well-defined collaborative task. This approach helps smoothing out the interaction between the user and the predicted movements generated from the system as it has learned to act like a real human.

In order to train the system to predict user's interactions, two well-known methods have been applied: Nonlinear Autoregressive models with eXogenous input (NARX) using the Levenberg – Marquardt algorithm as a training algorithm and deep learning using a Long Short-Term Memory (LSTM) neural network. Nine datasets have been used for the training and one dataset for the validation of trained networks.

8.1.1 Artificial Neural Network

Throughout history, human beings have always been urged to create new tools and machines that might help them to improve their potentialities. In the past, people believed that machines only could do what people told them to do. However, the appearance of the computer has changed this thought. After some decades, modern computers are making "Artificial Intelligence" (AI) – the term first introduced by John McCarthy in 1956- possible. Although people have not reached the ultimate goal of AI which is to create machines that could "think, learn and create", the development of AI has been increased dramatically with a lot of theories such as Von Neumann's

sequential system philosophy, biological neural networks, ANN, etc. (Rabuñal & Dorado, 2006)

Artificial neural networks (ANNs) are inspired by biological neural networks; thus, they contain some essential characteristics of AI that are missing in Von Neumann's theory (e.g., massive parallelism, learning ability, generalisation ability, etc.). ANNs require knowledge from diverse disciplines such as computer science, neurophysiology, AI, mathematics, etc. (Jain et al., 1996)

8.1.2 Historical development of ANN

The development of ANN could be divided into three periods: McCulloch and Pitts' study in the 1940s, Rosenblatt and Minsky's study and Papert's studies in the 1960s, and the other works of multiple researchers (e.g., Hopfield, Werbos, Rumelhart et al., etc.) in the 1980s (Jain et al., 1996). The study of McCulloch and Pitts in 1943 began the dawn of cybernetics as well as the ANN. They not only proposed logic or abstraction as concepts that machines could use but also a model for artificial neurons. The learning system and this model came together and then became the foundations of connectionist systems. According to Hebb Rule-where, most of these systems derived from-whenever a connection between neurons is used; this connection is reinforced (Rabuñal & Dorado, 2006).

The study of Rosenblatt and Minsky was the perceptron and convergence theorem of Rosenblatt. The perceptron is a model that provides a learning

system and is capable of recognising patterns. It produces the answers or results based on the action of inputs (Rabuñal & Dorado, 2006). Nevertheless, Minsky and Papert pointed out a simple perceptron's limitations in 1968. The research of Minsky and Papert has affected the enthusiasm of ANN researchers in computer science for almost 20 years. In the 1980s, the works of some researchers, such as Hopfield's energy approach and the back-propagation learning algorithm for multilayer perceptrons popularized by Rumelhart et al., have brought the new interest for ANN research (Jain et al., 1996).

8.1.3 Mathematics and algorithms principles

An ANN consists of a set of processing units that can receive or send signals to each other over numerous weighted connections, i.e. a processing unit receives input from either its neighbours or external sources and then computes and sends an output based on this information. The ANN system ensures that many units can do their tasks simultaneously (Krose & Smagt, 1996). The most attractive feature of ANN is the ability to learn. Generally, the learning process of an ANN can be understood as the corrections of its weighted connections and architecture based on sample training patterns. The performance of this ANN then can be improved after each time of its weighted connections update. ANN can have a single layer or multilayer (Jain et al., 1996). The perceptron of Rosenblatt is the best representative of single layer ANN. Following example is the learning process of single layer ANN with the perceptron as a learning algorithm:

Suppose there is a very simple single-layer network with one output and two inputs:
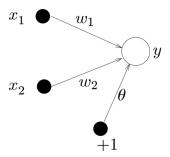
Figure 8.1: Single layer network (Adapted from Krose & Smagt, 1996)

In figure 8.1, there are two inputs x_1 and x_2 with their respectively weighted factors w_1 and w_2. The neuron's input is the weighted sum of two inputs x_1, x_2 plus bias term θ. The function represents the output of this network:

$$y = \mathcal{F}\left(\sum_{i=1}^{2} w_i x_i + \theta\right),$$

(26)

In this example, the activation function selected is a threshold function which represents the output of this network; this output depends on the input:

$$\mathcal{F}(s) = \begin{cases} 1 & \text{if } s > 0 \\ -1 & \text{otherwise} \end{cases}$$

(27)

Because the output of this network can be either +1 or -1, this kind of ANN is best used for classification tasks. The value of output will be computed

based on the total values of inputs. The following equation represents a straight-line separation between two classes in this example:

$$w_1 x_1 + w_2 x_2 + \theta = 0 \qquad (28)$$

The new weighted values can be updated as follows:

$$\begin{aligned} w_i(t+1) &= w_i(t) + \Delta w_i(t), \\ \theta(t+1) &= \theta(t) + \Delta \theta(t). \end{aligned} \qquad (29)$$

In order to classify the input precisely, $\Delta w_i(t)$ and $\Delta \theta(t)$ need to be computed. The question is: how can they be computed? Fortunately, the perceptron provides an algorithm to answer this question. If there is a desired output for this network called d(x), the method of the perceptron learning algorithm can be described as follows:

- Step 1: Initialise random weights with small values for connections

- Step 2: select a vector x from a set of sample training patterns as an input.

- Step 3: If $y \neq d(x)$ i.e. the response does not match desired output, changing all connections w_i by applying: $\Delta w_i = d(x)x_i$;

- Step 4: Go back to step 2.

The θ is also understood as a connection w_0 of the constant input $x_0 = 1$ and the output neuron. Hence, this θ can also be modified by applying the above steps:

$$\Delta\theta = \begin{cases} 0 & \text{if the perceptron responds correctly;} \\ d(\boldsymbol{x}) & \text{otherwise.} \end{cases}$$

(30)

Nevertheless, the single-layer perceptron has limitations. The largest one has been pointed out by Minsky and Papert's work that a single layer perceptron could not represent an exclusive-or function. In order to solve this problem, hidden units have been introduced (Krose & Smagt, 1996). For example, the single-layer network in figure 8.1 can be transformed into the multilayer network in figure 8.2:
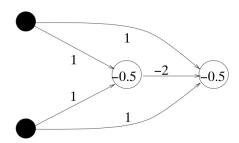
Figure 8.2: the neural network in figure 8.1 with an addition hidden unit (Adapted from Krose & Smagt, 1996)

The perceptron algorithm is a fundamental to develop a much more robust and widely used algorithm: backpropagation algorithm.

8.1.4 Backpropagation algorithm

This is an essential learning algorithm which is applied as a core algorithm for neural networks used in this thesis – backpropagation algorithm. General speaking, this algorithm back propagates the errors of output neurons to determine the errors of hidden neurons. The activation function

is usually used for this algorithm is a sigmoid function. This algorithm's method can be described as follows (Jain et al., 1996; Krose & Smagt, 1996):

- Step 1 & 2: The same as the perceptron algorithm described above.

- Step 3: Compute error signal for an output unit by:

$$\delta_o^p = (d_o^p - y_o^p)\, y_o^p (1 - y_o^p).$$

(31)

- Step 4: Compute error signal for a hidden unit by propagating the errors backwards:

$$\delta_h^p = \mathcal{F}'(s_h^p) \sum_{o=1}^{N_o} \delta_o^p w_{ho} = y_h^p (1 - y_h^p) \sum_{o=1}^{N_o} \delta_o^p w_{ho}.$$

(32)

- Step 5: Update weights by applying:

$$\Delta_p w_{jk} = \gamma \delta_k^p y_j^p.$$

(33)

- Step 6: Go back to step 2. The iterations repeat until the error of output neuron is lower than a pre-specified threshold or reach a maximum number of iterations.

The backpropagation algorithm is commonly used in ANN with multiple layers. The design of an ANN can go from very simple with single layer feed forward network to very complicated recurrent competitive networks. The next section introduces some common designs of ANN.

8.1.5 Common designs of ANN

The architecture of an ANN can be either a feed-forward neural network (FNN) or a recurrent neural network (RNN). In designs of feed-forward networks, the graphs have no loops and unidirectional connections between neurons. Moreover, feed-forward networks called static because they only produce output values as a set instead of a sequence from an input. On the other hand, the graphs of recurrent/ feedback networks have loops because of their feedback connections. Also, these networks called dynamic because they contain feedback paths; thus, the networks can enter a new state by modifying the inputs of each neuron. Figure 8.3 presents the taxonomy of two kinds of networks stated above. Figure 8.4 presents some common types of activation functions: (a) threshold, (b) piecewise linear, (c) sigmoid, (d) Gaussian.
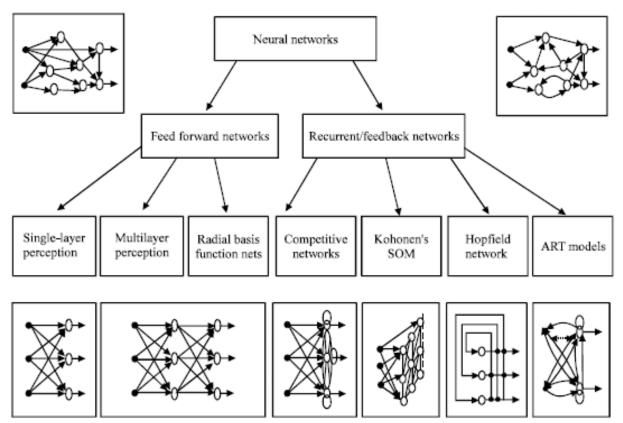
Figure 8.3: A taxonomy of feed-forward and recurrent/ feedback networks (Adapted from Jain et al., 1996)
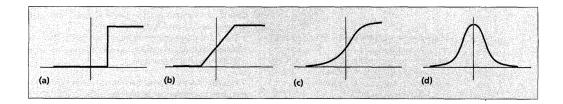
Figure 8.4: Common types of activation functions: (a) threshold, (b) piecewise linear, (c) sigmoid, (d) Gaussian (Adapted from Jain et al., 1996)

8.1.6 Classification

Nowadays, ANN is applied to a lot of different disciplines. According to Jain et al. (1996) the applications of ANN are for solving these following seven problems:

1. Pattern classification

2. Clustering/ categorization

3. Function approximation

4. Prediction/ forecasting

5. Optimisation

6. Content-addressable memory

7. Control

8.1.7 NARX networks

Artificial neural networks (ANNs) have been used for a range of applications such as time series predictions, classification, recognition, optimisation, etc. (Kim et al., 2004; Duro and Reyes, 1999; Araujo et al., 2017; Gong et al., 2017; Sanchez et al., 2017). ANN models are particularly beneficial for time-series predictions with noisy and nonlinear data. They usually outperform other standard linear techniques, e.g. Box-Jenkin models (Box et al., 1994) for such system thanks to their capability of nonlinear mapping of m-dimensional inputs onto n-dimensional outputs while the relationship

between the inputs and outputs are unknown (Yu et al., 2012) and better robustness to noise (Xie et al., 2009).

Nonlinear autoregressive models with exogenous inputs (NARX) is a well-known subclass of the recurrent dynamic neural architectures. NARX networks have been proven to be computationally powerful in theory (Siegelmann et al., 1997) and a good predictor for time series (Mohanty et al., 2015; Pisoni et al., 2009; Ruiz et al., 2016).

The NARX network, described by equation 28, predicts a time series Z at time t using as regressors the last p values of an external variable U and the last p values of the series itself. The non-linear function f represents a feedforward network architecture and its weights. The input layer is usually known as the time window.

$$Z(t) = f\big(U(t-1)\dots U(t-p)\dots Z(t-1),\dots,Z(t-p)\big) + e(t) \qquad (34)$$

The Levenberg-Marquardt (LM) algorithm is one of the most well-known algorithms for optimasation. The results from LM in most of the problems are usually significantly better than simple gradient or other conjugate gradient methods (Ranganathan, 2004). LM is a combination of vanilla gradient descent and Gauss-Newton iteration.

The Levenberg–Marquardt algorithm (provided by MATLAB neural network toolbox) have been applied to adjust the weights of the ANNs. The algorithm is presented as follows:

$$w_k = w_{k+1} + \Delta w \qquad (35)$$
$$\Delta w = [J_k^T J_k + \eta I]^{-1} J_k e_k \qquad (36)$$
$$\boldsymbol{e_k = r_k - z_k} \qquad (\textbf{37})$$

Where w is the weight vector, Δw is the difference between the weight vectors, J is the Jacobian matrix that contains the first derivatives of the network errors with respect to the weight, η is a scale parameter, I is the

identity matrix, R is a vector of the reference motion, z is a vector of the estimated motion, and e is a vector of network errors.

8.1.8 LSTM neural network

A recurrent neural network (RNN) is a class of neural network which is derived from feedforward networks. While in a feedforward network, information can only move in one direction, a RNN can allow information to flow through a cycle as a loop. This looping mechanism comes together with its internal memory makes the RNN very good at predicting sequential data since it can consider the inputs from both current and previous steps.

By the late 1980s, several pieces of research (Hecht-Nielsen, 1989; Jordan, 1986; Hornik et al., 1989) had pointed out that a backpropagation algorithm is very difficult to be applied to train traditional deep feedforward/ recurrent neural networks (FNNs/ RNNs). The primary reason has been identified by Hochreiter (1991) known as the long-time lag problem: computed errors from the backpropagation algorithm (as mentioned in section 8.2.3) are either quickly shrunk or exploded (growing out of bounds). Supervised Long Short-Term Memory (LSTM) RNNs have been introduced (Gers et al., 2000; Pérez-Ortiz et al., 2003; Hochreiter & Schmidhuber, 1997) to overcome this problem.

A LSTM network has a memory cell which can remember information from previous timesteps and three gates (input, forget and output gate) that determine (by using sigmoid function) which information is allowed to pass through the cell state (input gate), stored or deleted (forget gate), and selected for the output (output gate). The equations for gates in a LSTM network are presented as follows:

$$i_t = \sigma(w_i[h_{t-1}, x_t] + b_i) \qquad (38)$$

$$f_t = \sigma(w_f[h_{t-1}, x_t] + b_f) \qquad (39)$$

$$o_t = \sigma(w_o[h_{t-1}, x_t] + b_o) \qquad (40)$$

Where i is the input gate, f is the forget gate, o is the output gate, t is the current timestep, σ is the sigmoid function, w is the weight for the gate, h is the output of the LSTM network, x is the current input, and b is the bias for the gate.

The idea behinds LSTM is very straight forward: each activation function c (called constant error carousel - CEC) is used as a node in a memory cell at timestep t and connects to itself with a fixed weight of 1.0. Back propagated errors going through a CEC cannot shrink or grow out of bounds (unless not going through a CEC but to other neural network's adaptive parts) because of the constant derivative of 1.0 from the function c. Nonlinear behaviour can be learnt by different nonlinear adaptive units that are connected to CECs, and some have multiplicative activation functions. Without CECs, previous RNNs had failed to memorise events even only ten of discrete time steps ago while LSTM neural networks can trace back events that happened thousands of time steps and change the weight accordingly. The CEC c, its candidate $\tilde{c}$, and the final output h are represented as follows:

$$\tilde{c}_t = tanh(w_c[h_{t-1}, x_t] + b_c) \qquad (41)$$

$$c_t = f_t * c_{t-1} + i_t * \tilde{c}_t \qquad (42)$$

$$h_t = o_t * \tanh(c^t) \qquad (43)$$

LSTM can also be applied in many different variants and topologies that use modifiable CECs with self-connections (Bayer et al., 2009; Gers & Schmidhuber, 2001).

8.2 Methods

8.2.1 Study design

Twenty-four naive healthy participants were recruited (mean age: 26.36, standard deviation: 5.76; gender: 8 females and 16 males) to work in pairs (randomly formed) to lift cubes in a shared virtual environment and stack them on the top of each other (Fig. 7.14 and 7.15). All pairs and participants were then numbered from 1 to 12 and 1 to 24 respectively (e.g., pair 1 includes participant 1 and 2).

Participants performed the task using a Phantom Omni – a robotic interface with haptic feedback – and allowed to talk to each other to complete the task successfully (chapter 7). Participants were instructed to collaborate with each other by using the Phantom Omni haptic devices to control his/her own virtual styluses to stack the cubes on top of each other (see Fig.1 and Fig. 2).

Position, orientation, and force data was collected during their interactions while performing the task. The data was collected at every frame of the application and since the application was running at 60 frame per second (fixed framerate), it means there were 60 data points recorded per second. The position data recorded was x, y, and z linear acceleration; the force data was the magnitude of interaction force in Newton; and the orientation data was x and z Euler angle; all data was fitted into fixed windows of 2.13 seconds (128 timesteps) for the network training.

All participants were provided written informed consent and this study was approved by Middlesex University research ethics committee on January 21st, 2015.

8.2.2 Training

Twelve datasets were recorded but only nine datasets were used due to missing data of three datasets (pair 1,2 and 11, failed to complete the task hence data collected was insufficient for network training). Eight datasets (pair 3 to 10) have been used to train the networks and one dataset (pair

12) has been used for testing. The first participant's data from each pair was used for the input while the second participant's data was the output (e.g., in pair 3, participant 5's data was the input and participant 6's data was the output). The predictor can predict the interaction forces, positions, and orientations of the virtual stylus from one participant based on his/her partner's inputs; the error of this training process called training error, as shown in Fig. 8.5. The estimation from this predictor could help to maintain the smoothness of the interaction via a high-latency network condition. In order to optimise the training, a simulation has been performed to determine the optimal number of hidden neurons. There was one predictor created for each number of hidden neurons (from 1 to 20), the error from the training process was called train error; and the performance of each predictor was tested using the remaining dataset the error was called test error in Fig. 8.5.

The predictor's performance was determined by calculating the normalised mean squared errors (NMSE). To have a better result in the real-time experiment, the value of test error should be minimum (Choi et al., 2010; Hastie et al., 2001). As shown in Fig. 8.5, when the number of hidden neurons was over 12, the training was over-fitted as the test error increased significantly. Thus, the predictor trained with 12 hidden neurons was selected.

8.2.3 Results

Figure 8.6-8.17 shows the estimated data (forces applied, positions, and orientations of the virtual stylus) generated by the predictor (trained by two different methods) versus the real data collected from the participants (dataset of pair 12). Fig. 8.18 shows the cube's trajectories in 3D space and 3D representations of objects and tools from real data, as well as estimations from LSTM and NARX methods. The orientations of the virtual tool were recorded in Euler angles. In Unity – the software used to simulate the virtual environment and collect data – Euler angles are determined by the rotations performed around individual axes following this order: The Z axis, the X axis, and finally the Y axis. Because in this trial, there was no roll

movement of the tool performed thus, the rotation of the Y axis was fixed and no orientation data has been recorded for this axis.

Table VIII shows the errors on each value tested from LSTM and NARX methods. It clearly states that when changing the method from NARX to LSTM, the errors were greatly reduced which indicates that the LSTM method was much more accurate to predict user's interaction for this task than NARX.

Overall, the results showed that deep learning with LSTM algorithm was significantly better (53.57% better in forces, average 64.77% better in positions and 51.1% better in orientation) than NARX with LM algorithm. Data generated from NARX network was not enough to complete the task successfully (force applied and position/orientation from AI agent were not accurate enough to help the human agent), while deep learning with LSTM showed the results that were very close to human interactions (was able to fulfil the task successfully within 25 seconds against 23 seconds as seen in real data).
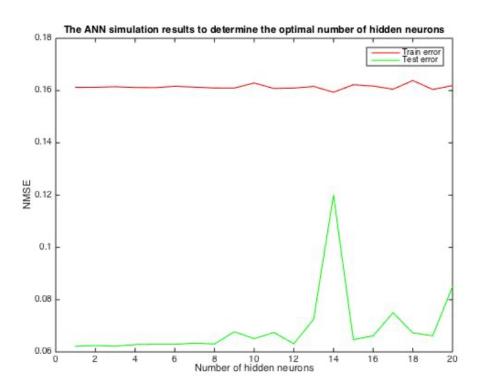
Figure 8.5: ANN simulation of interaction forces to determine the optimal number of hidden neurons

Table VII: RMSE results on the values of LSTM and NARX methods

Values	NARX	LSTM	Reduced
Forces	F=1.40	F=0.65	-0.75 (-53.57%)
Positions	X=0.52 Y=0.56 Z=3.40	X=0.18 Y=0.37 Z=0.17	-0.34 (-65.38%) -0.19 (-33.93%) -3.23 (-95%) Avg. -64.77%
Orientations	X=12.8 Z=293.2	X=11.3 Z=27.9	-1.5 (-11.72%) -265.3 (-90.48%) Avg. -51.1%

Note. Reduced: Reduced in errors when changing NARX to LSTM.
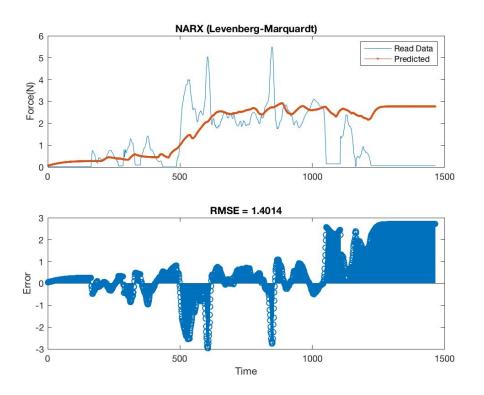
Figure 8.6: Forces estimation using NARX - top chart is the force applied in Newton during the trial while bottom chart indicates errors in real time and the RMSE.
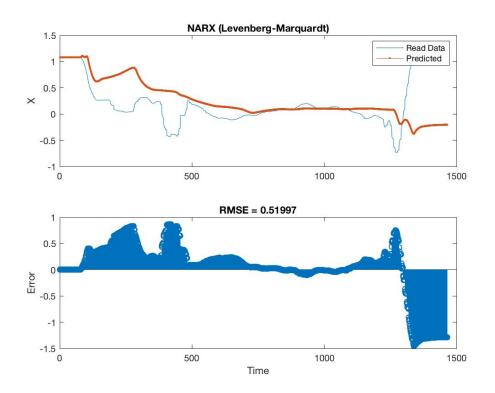
Figure 8.7: X position estimation using NARX - top chart is the position of the tool (X axis) used by the participant during the trial while bottom chart indicates errors in real time and the RMSE.
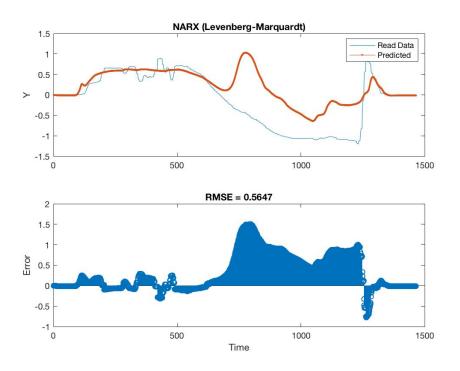
Figure 8.8: Y position estimation using NARX - top chart is the position of the tool (Y axis) used by the participant during the trial while bottom chart indicates errors in real time and the RMSE.
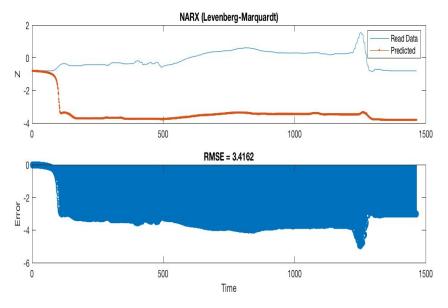
Figure 8.9: Z position estimation using NARX - top chart is the position of the tool (Z axis) used by the participant during the trial while bottom chart indicates errors in real time and the RMSE.
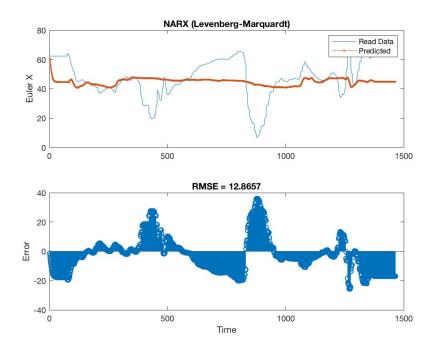
Figure 8.10: Euler X estimation using NARX - top chart is the Euler angle values of the tool (rotation around X axis) used by the participant during the trial while bottom chart indicates errors in real time and the RMSE.
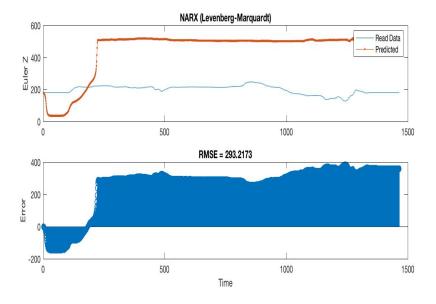
Figure 8.11: Euler Z estimation using NARX - top chart is the Euler angle values of the tool (rotation around Z axis) used by the participant during the trial while bottom chart indicates errors in real time and the RMSE.

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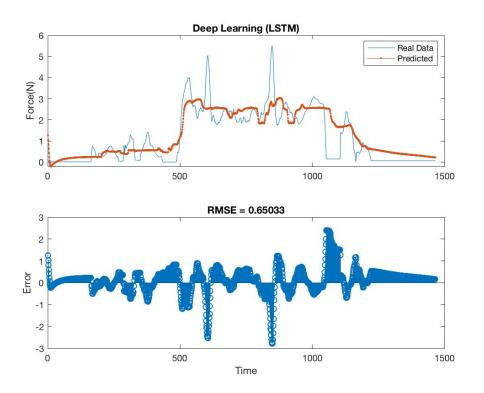
Figure 8.12: Forces estimation using Deep Learning (LSTM) - top chart is the force applied in Newton during the trial while bottom chart indicates errors in real time and the RMSE.
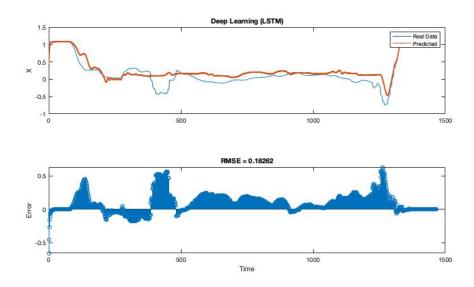
Figure 8.13: X position estimation using Deep Learning (LSTM) - top chart is the position of the tool (X axis) used by the participant during the trial while bottom chart indicates errors in real time and the RMSE.
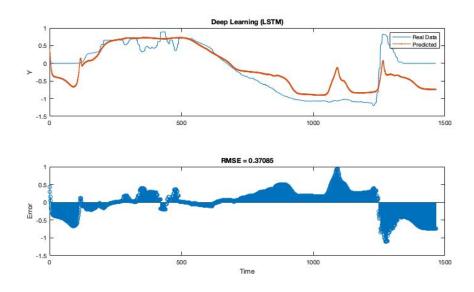
Figure 8.14: Y position estimation using Deep Learning (LSTM) - top chart is the position of the tool (Y axis) used by the participant during the trial while bottom chart indicates errors in real time and the RMSE.

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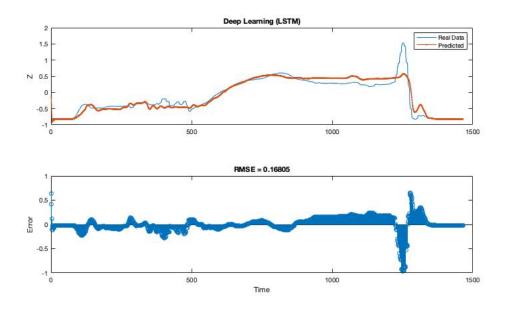
Figure 8.15: Z position estimation using Deep Learning (LSTM) - top chart is the position of the tool (Y axis) used by the participant during the trial while bottom chart indicates errors in real time and the RMSE.
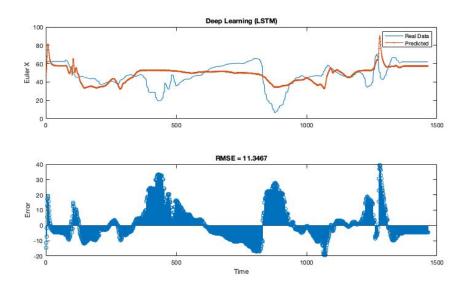
Figure 8.16: Euler X estimation using Deep Learning (LSTM) - top chart is the Euler angle values of the tool (rotation around X axis) used by the participant during the trial while bottom chart indicates errors in real time and the RMSE.

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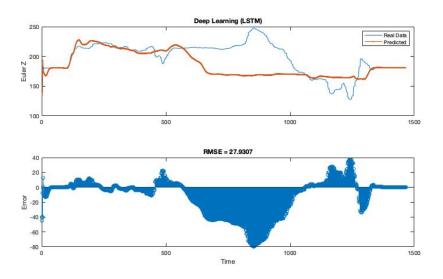
Figure 8.17: Euler Z estimation using Deep Learning (LSTM) - top chart is the Euler angle values of the tool (rotation around Z axis) used by the participant during the trial while bottom chart indicates errors in real time and the RMSE.
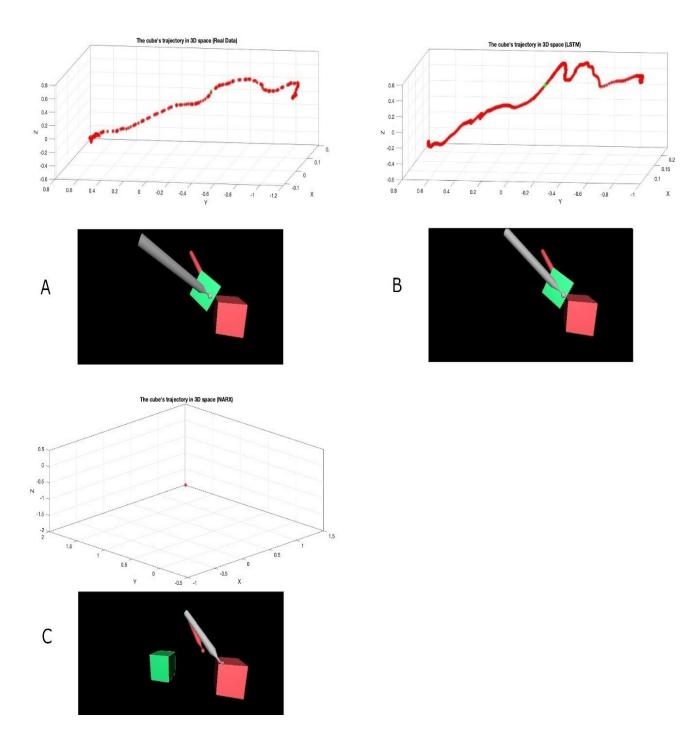
Figure 8.18: The cube's trajectories in 3D space (top figures – trajectories of the cube from start to finish) and 3D representations of the objects and tools (bottom figures, halfway until completion of the task, marked as green points in top figures). A) Real data. B) Estimation from LSTM, completed the task successfully. C) Estimation from NaRX, failed to complete the task hence there was no trajectory for the cube.

8.2.4 Discussions

Results from LSTM show a great potential to predict user's behaviour to reduce the negative effects of network delay. A simulation has been run in Unity 3D with LSTM algorithm as a predictor. The remaining dataset collected from the participants (completely different from the eight datasets using for training) has been used as a test data. In this dataset (pair 12), the first participant's data was used as input while the second participant was replaced by the AI agent. The results of the NARX network may be improved by applying a different learning algorithm. The LM algorithm used in this study might not be suitable for this particular task.

When it comes to the LSTM network, the task could be finished successfully even though the data from one user was completely missing (Fig. 8.18B shows that the estimation from LSTM can fulfil the task thus the trajectory of the cube in 3D space was recorded). This result suggests a new approach: all haptic data can be rendered locally to reduce the amount of data being transmitted via the network while a predictor can help to compensate the user's input loss. This approach would take advantage of both predictor and synchronisation control schemes methods mentioned in chapter 4 - section 4.3.1.

The cooperative task introduced in this study can fit the cooperative bilateral interaction for telerehabilitation as mentioned in the introduction section. Since therapeutic exercises for rehabilitation are usually repetitive and have a specific goal (e.g., moving an object or reaching a shelf) that are similar to this particular task, it is potential to apply this method to those exercises

It is also worth to mention that when two participants were working on this collaborative task, they have had to communicate to each other to come up with a consensus strategy in order to fulfil the task. The predictor has completely removed this requirement since all the input data from one participant is generated by the algorithm. As a result, it has made the task

easier to complete and eliminated the social interaction between two participants. Hence, the predictor should only be used as a last resort to support the telerehabilitation system when the network condition is poor.

The results from the simulation have proven Hypothesis 2: LSTM method is appropriate for this collaborative task and can help to predict missing data from one user.

8.3 Chapter summary

This chapter compares the predictor's performances from two well-known but distinctive algorithms for a collaborative task in a virtual environment via network connection. The simulation results from this chapter suggest that by applying an appropriate algorithm, the predictor can help to complete the task successfully. It could be very useful to apply this method to similar existing therapeutic exercises that require haptic feedback thus making the telerehabilitation available despite the network condition.

Chapter 9: Conclusions and recommendations

Chapter 9 summarises the results and the contributions of the research presented in this thesis. Hypotheses are revisited and concluded, limitations of the research are considered, and recommendations learnt from studies in this thesis are also proposed.

9.1 Summary of findings

The table below summarises each study has been done in this thesis. All studies' descriptions, objectives and findings can be cross-referenced to the corresponding chapter.

Chapter	Study	Description	Objectives	Findings
6.1	Robotic bells study	Participants interacted with a haptic robot (Novint Falcon) and Microsoft Kinect in 3 different phases (Conventional Haptic Interaction, Haptic Photo Booth, and Robotic Bell)	Examine how group interactions re-shape the individual's mental model while interacting with a robot that plays a bell attached to its end-effector as the user executes three-dimensional arm movements.	Results suggest that indeed this type of approach can be fun, increase participation of individuals in the group task and seem to contribute to re-shaping of an initial mental model through group collaboration. Incidentally, the results appear to suggest that as a consequence of the group dynamics, subjects tend to make more movements than expected for such a small length of time.
6.2	Interactive painting			

	(healthy participants)		
Experiment 1	Participants explored a painting through haptic feedback with/without sonic interaction while performing movements with a haptic device (Novint Falcon) in three dimensions	Evaluate the participants' subjective experience when interacting with the painting with haptic feedback only versus haptic + sonic feedback	Results suggest that when exploring concepts of augmented artefact installations with technology (haptics + sound or just haptic), participants seemed to prefer to interact with haptic + sound over just haptic
Experiment 2	Participants were divided into a group of individuals and a group of pairs, they also interacted with another painting with different haptic feedback and sound.	Compare the participants' subjective experience when interacting with the painting as individuals versus pairs	The results suggest that participants engaged with the interactive installation and executed more movements while exploring the painting in pairs. It appears that the haptic painting paradigm encourages development of analytical skills, imagination,

				promotes spatial skills realisation and enhances touch/hearing sensory channels.
6.3	Interactive painting (Autistic children)	Participants explored an interactive painting through haptic and sonic feedback using a haptic device (Phantom Omni) in three dimensions	Evaluate the participants' behaviour and experience while interacting with the painting as individuals versus as groups	The results suggest that the autistic children were engaged with the interactive painting and had some positive interactions with other children.
7	Collaborative cube study	Participants worked in pairs to lift cubes (both virtual and real objects) and stack them on the top of each other in an unspecified order and following a specific sequence (e.g. lift cube A on top of cube B or	Investigate how different environments (real vs. virtual) and communication modalities (with vs. without talking to each other) affect the quality of interactions between humans	The results suggest that doing the task in the virtual world was more difficult and required more effort to complete than doing it in the real world. The communication was crucial to finish the task successfully in virtual world due to the loss of depth

		cube B on top of cube A)		perception in virtual domain. It also suggests that working in the virtual world is more interesting than doing the same task in the real world.
8	NARX and LSTM methods for predicting user's interaction Study	Two distinctive training methods (NARX and LSTM) were applied for modelling user's interactions from collected data in chapter 7	Compare the performance of each method and find the appropriate one for this particularly collaborative task.	Results from LSTM show a great potential to predict user's behaviour to reduce the negative effects of network delay for the cube lifting task in chapter 7 via virtual domain. The artificial predictor (trained by LSTM) can perform very well by allowing the predictor to complete the task within 25 seconds versus 23 seconds when performed by the human.

9.2 Conclusions

From a practical perspective, the developed haptic framework itself is novel and significant. It introduces a new approach for socially assistive robotics, which is using haptic robots as mediators to promote group interaction between human users, while most of the research up to date only focuses on human-robot interaction. Its abilities to generate playful activities for multiple participants in different social, environmental settings and collect quantitative data are also novel in the field thus have the potential of being beneficial for stroke rehabilitation and autism intervention.

In general, the results obtained from the studies presented in this thesis are promising and encouraging. Participants seemed to be more engaged in a group and made more movements than if they did it on their own, thus group interaction seemed to have positive influence on participants. It also highlights the social potential of the developed framework: activities are indeed playful and engaging while during the activities participants have the tendency to discuss the experience to each other (in the case of autistic children, they have had to 'negotiate' to take turn to use the device).   The capability of the framework to be applied in multiple social environments is also worth mentioning: the tasks generated from the framework seemed to work well in different settings (lab-based environment, art gallery, virtual environment). The responses from the participants regarding haptic and sound feedback are also positive. Most participants reported having experienced realistic feelings with the experiments and the sonic/haptic feedback meet their expectations. In addition, following notes are things that we can learn from those studies and should be taken into account for future study design:

The study in chapter 6 – section 6.1 implies that a clear goal for a collaboration task (work together to figure out how to make a robot to play

a bell) does not require any specific instruction but still encourages people to work more and increases their attention. It is due to the fact that they have many options and discussion is needed to choose the right one. For instance, as presented in section 6.1, the robot could only track one hand at a time and the participants were not informed about this limiting feature, thus they discussed substantially more the strategies while trying to figure out how to control the robot. This kind of task is also more beneficial in terms of motor learning since variability in task may result in a longer retention and increase the chance of generalisation. This study has contributed an investigation on the effect of group interaction and playful activity in user's behaviours. The result suggests that group interaction re-shaped participants' mental models formed from previous individual tasks and encouraged users to perform movements.

The studies involving the haptic and sound painting (chapter 6 – section 6.2 and 6.3) show that a task without a particular goal needs a clear instruction or even demonstration to engage participants. The study with healthy participants (section 6.2) revealed that participants could lose their interests very quickly if they did not know what to do and what to expect from the system (the experiment with the ball painting – section 6.2.1). On the other hand, if the participants understand the feedback from the system corresponding to their actions, they could be engaged and therefore motivated to explore more (the experiment with the seaside painting – section 6.2.2). Those studies also suggest that a visual cue can be removed if there is an adequate compensation from sound and haptic feedback (without visual feedback, participants still enjoyed and recommended the experience as stated in their questionnaires – please refer to Appendix A, questionnaires for more information). This study has contributed an investigation on the difference of user's interactions with haptic/audio feedback while they are on their own or in a group. This investigation helps to have a better understanding of human behaviours in complex tasks and social environments that is very limited in the literature. The results show

that participants engaged with the interactive installation and were willing to spend more time while exploring the painting in groups.

The study with autistic children suggests that playful activity with innovative technologies similar to the interactive painting setup may encourage them to interact more. It has contributed an investigation on how group interaction with haptic and audio feedback affects children with autism. This study examines further the effect of group interaction with a playful activity in autistic children - a cohort with impairment in social interaction skills. It shows that when participants explored in a group, they had to communicate with each other and take turns to use the device which may raise an opportunity to develop their social skills.

The study in chapter 7 compares the collaborative task in both virtual and real environments expand the understanding of how participants react in the virtual domain. It has contributed an investigation on the differences of performance and user engagement between doing a collaborative task in the real-world with its counterpart in the virtual world using a haptic device. The results suggest that doing the task in the virtual world was more complicated and required more effort to complete than doing it in the real world even though the virtual world task was more engaging. The strategies to finish the task in each world were also different. It suggests that the depth perception is a crucial aspect which could heavily affect user's performance. However, it also suggests that group interaction in the virtual world has the potential to deliver an effective rehabilitation/intervention program for people with special needs. The understanding learnt from this investigation will probably help to develop a model that can predict the user's behaviours in a collaborative task.

The simulation results presented in chapter 8 suggested that deep learning with the LSTM algorithm could be used to create a good predictor to compensate for data loss during network transmission. It has contributed to the knowledge by providing a comparison between two well-known

training methods with collected data to predict user's behaviours in a collaborative task.

9.3 Hypothesis revisited

Central Hypothesis: Novel technologies mediated by social interaction can positively influence participants' interactions and engagement levels. By using those technologies, a real-life task involving social interaction can be transferred to a virtual domain and delivered remotely.

Proven

Results from section 6.1 showed that participants enjoyed the task while playing with the robotic bell, they made a lot of movements in a short period of time.

Results from section 6.2.1 showed that participants preferred more feedback i.e., haptic + sound rather than just haptic hence novel technologies will help to enhance their motivation.

Questionnaire results from section 6.2.2 showed that participants were willing to spend more time on the task if they can have some interaction with other people even though there was no significant difference found on the recorded time spent.

Results from section 6.3 showed that autistic children enjoyed exploring the painting and had some positive interactions with other children (e.g., 'negotiate' to each other to take turn)

Results from chapter 7 showed that participants enjoyed doing the task in the virtual world (using haptic technology) more than the real world even though it was much more difficult to do that.

Results from chapter 8 showed that LSTM training method can predict and compensate missing data from one user which will help to implement the task remotely via the internet.

However, the sub-Hypothesis 1 will need more evidence to prove.

Hypothesis 1: Playful interaction in a group modulated by a haptic interface will enhance engagement and motivation. As a result, participants will spend more time on the same task than they do individually.

The results from studies in chapter 6 do not prove this hypothesis. Even though Participants working as a group were willing to spend more time (when asked in questionnaire from section 6.2.2), there were no significant differences in the actual time recorded (section 6.2.2 and section 6.3).

Hypothesis 2: Collaborative behaviours can be effectively predicted from data collected from pairs of individuals using a haptic interface and the outcome of such prediction should be close to the real interaction.

The results showed in chapter 8 seem to support this hypothesis especially when using the deep learning training method. The simulation shows that the task can be completed successfully with the predictor trained (deep learning method) from real data. It also shows that there are no significantly different interactions between the predicted data and the real data.

9.4   Limitations of the research

The main limitation of this research was that it did not involve any post-stroke patients due to the time constrains and low budget. As a result, this research did not have any clinical results to suggest an effective training session that can support patients after stroke.

Another limitation was that this research did not test all the benchmarks to evaluate the framework presented in chapter 5. Therefore, the developed haptic framework could be unoptimised and may not be suitable for some applications.

One possible criticism is that the predictor implemented in chapter 8 has not been applied in any real-time interaction, thus the behaviours and reactions from human agent while interacting with the AI still remain unknown.

Another limiting factor was that this research did not include cooperation and competition strategies into the task. This meant that the user's behaviours in group interaction presented in this thesis is limited to a collaborative interaction and cannot at present be generalised for all types of interactions.

9.5 Recommendations

A suggestion for future work is to investigate the difference in terms of performance and engagement between virtual and real environments for different types of group interaction in motor learning literature such as

cooperation task (users have different roles) and completion task (users have different goals). This together with conducted study from this thesis will help to generalise user's behaviours when interacting in a group which will remarkably enhance the ability to predict user's strategy to complete the same interactive task.

Another suggestion is to apply VR technology to compensate user's depth perception while doing the task in virtual environment. This examination will determine whether depth perception actually improve user's performance and bring the strategy to finish the task closer to the one in the real world.

A final suggestion is to apply the predictor model implemented in chapter 8 in real-time application. The predictor can have 2 modes:

- Active-assisted: this mode will be enabled when the system detects a huge delay in the network which makes it impossible to update the end-effector positions in the real time. The predictor will help by selecting the best solution based on user's profile. In particular, subject will need to make the initial move, the system then guesses the contact point between the end-effector and the object learned from his or her own historical movements and move the end-effector to that contact point. Haptic feedback will be generated correspondingly to match the time frame i.e. there is no movement correction in this mode, the subject only needs to initialise his or her movement and everything else will be generated automatically. Although this does not provide the real interaction for the participants, it can still enable participants to practise in a very poor network condition.

- Active: The mode is enabled in a medium delay network condition e.g., the end-effector still can be updated in real time; however, it is not fast enough to have smooth haptic feedback. In this mode, participants can move their end-effector freely to choose the contact point. Once a contact point is chosen, the system will adjust subject's

movement by comparing their real time end-effector's position and the similar (or closest) one learned before to maximise the natural feel of interaction. The haptic feedback will be produced based on the pre-learned position locally to ensure the smoothness.

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Appendix A: Questionnaire Data

Protocol for "Into the Frame" concept demonstrator trial

Number of participants: 24

Number of questionnaires: 2 (one per experiment)

Trial estimated time per participant: 10 minutes

Logged data: Position (XYZ), Force (XYZ) and Acceleration/Velocity (XYZ), Time, Video form 4 cameras

Equipment:

- 2 Laptops running Windows
- 1 Novint Falcon
- 4 Camcorders

Inclusion criteria:

Healthy people who know how to operate a computer.

Participants with significant visual and cognitive impairments are excluded.

Study design:

At least 24 healthy participants will be recruited from Middlesex University to conduct an experiment that involves interacting with a painting using a haptic device. The study will consist of a series of 24 single case studies. The

study will comprise two experiments and participants will be recruited to either one of the experiments. Experiments are as follows:

1. Experiment 1 (painting: Sphere): Participants will be divided into two equally numbered groups. Each group is involved in two different phases:
   a. Phase A, will consist of a subject exploring a painting using haptic interaction while grasping the Novint Falcon robot.
   b. Phase B, will consist of a subject exploring a painting using haptic and sonic interactions while grasping the Novint Falcon robot.
2. Experiment 2 (painting: Sea landscape): participants will be divided into two equally numbered groups and will be exploring a painting using haptic and sonic interactions while grasping the Novint Falcon robot. Groups are as follows:
   a. Singles, participants interact with the painting on their own
   b. Pairs, participants interact with painting while cooperating with another subject

At the end of each experiment participants will be asked to fill a questionnaire survey rating the experience. Participants will be randomized in to one of the two phases in experiment 1 to see if there are any differences in preference vs. expectancy related to the order of the phases. At all times four camcorders will be recording each participant's interactions.

Procedure:

To start with, the user is informed that will be exploring an interactive painting using a haptic device for an undetermined period of time and once satisfied; the user needs to fill in a questionnaire survey.

Experiment 1:

Participants will be assigned to one of two groups randomized into two phases:

Group 1: AB

Group 2: BA

Experiment 2:

Participants assigned to two groups.

Group 1: singles, users instructed to explore the interactive painting

Group 2: pairs, users instructed to explore together the interactive painting

Outcome measures and data collection:

Participants will be assessed through a questionnaire using the methodology suggested by (O'Brian and Toms, 2008) which evaluates some specific aspects of user experience and engagement, such as Endurability (the likelihood of remembering an experience and willingness to repeat it), Usability (the ease of use and learnability of a human-made object) and Focused Attention (attention to the exclusion of other things). In addition audio-visual data from the interaction resulting from the experiments will be collected using four camcorders while, kinematic data (positions, velocities), and time are recorded using the robot (Novint Falcon).

O'Brian, H & Toms, E., 2008. What is user engagement? A Conceptual Framework for Defining User Engagement with Technology. JASIST, 59(6), pp. 938-955.!

Questionnaire – Experiment 1

Name:_____Age:_____ Sex:_____

Subject No. _____ Group:_____

For each of the following statements, please indicate how true it is for you, using the following scale:

1	2	3	4	5	6	7
not at all			somewhat			very
true			true			true

1. I would be more likely to visit exhibitions where the interactive paintings are available.	
2. This installation made the art more enjoyable.	
3. It was easier to navigate through the painting without sound.	
4. I found the device was easy to use while interacting with the painting.	
5. I'd like a chance to explore the interactive painting again.	
6. Touch + Sound together made the experience more interactive and engaging than just Touch itself.	
7. I noticed more about the painting using this device than I would without it.	
8. When touching the ball from the right hand side, I could hear the sound in my left ear.	

Please answer the following questions:

1. How many times during the previous year have you visited an art gallery/ museum? (tick as appropriate)

   - ❒ None

   - ❒ 1-5

   - ❒ 5-10

   - ❒ More than 10

2. How many different sounds could you identify while interacting with the painting? (tick as appropriate)

   - ❒ 1

   - ❒ 2-5

   - ❒ 5-10

   - ❒ More than 10

3. How long do you think you could explore the painting before it would become boring?

   Only Touch _____   Touch + Sound _____

4. Do you have any suggestions or recommendations for future trials?

   _____

   _____

   _____

   _____

   _____

Thank you very much for taking your time to participate in this pilot study.

Questionnaire – Experiment 2

Name:_____Age:_____ Sex:_____

Subject No. _____ Group:_____

For each of the following statements, please indicate how true it is for you, using the following scale:

	1	2	3	4	5	6	7
	not at all			somewhat			very
	true			true			true

1.	I would be more likely to visit exhibitions where the interactive paintings are available.	
2.	This installation made the art more enjoyable.	
3.	It was easier to navigate through the painting without sound.	
4.	I found the device was easy to use while interacting with the painting.	
5.	I'd like a chance to explore the interactive painting again.	
6.	Exploring the interactive painting with the other participant made the experience more enjoyable.	
7.	I noticed more about the painting using this device than I would without it.	
8.	When touching the water from the right hand side, I could hear the sound in my right ear.	

Please answer the following questions:

1. How many times during the previous year have you visited an art gallery/ museum? (tick as appropriate)

   ❐   None

   ❐   1-5

   ❐   5-10

☐ More than 10

2. How many different sounds could you identify while interacting with the painting? (tick as appropriate)

     ☐ 1

     ☐ 2-4

     ☐ 4-6

     ☐ More than 6

3. How long do you think you could explore the painting before it would become boring?

     Alone_____   In a group _____

4. Do you have any suggestions or recommendations for future trials?

_____

_____

_____

_____

_____

_____

Thank you very much for taking your time to participate in this pilot study.

NOT TO BE SHOWN TO THE SUBJECT:

1) Endurability: 1, 5, 8
2) Focused attentions: 3, 6, 7
3) Usability: 2, 4

Responses

Questionnaire, EXPERIMENT 1

Subject	Group	Age	Sex	1	2	3	4	5	6	7	8	Question 1 (A,B,C,D)	Question 2 (A,B,C,D)	Question 3 Only Touch (Seconds)	Question 3 Touch + Sound (Seconds)
1	A	28	M	5	4	6	4	7	7	2	2	B	B	60	180
2	B	21	M	6	4	1	4	7	6	4	1	A	B	5	10 - 15
3	A	24	M	5	5	3	6	7	7	7	7	B	A	180	5
4	B	20	M	6	6	7	4	5	7	5	3	A	B	60	180
5	A	23	M		5	1	3	4	7	7	7	A	B	20	60
6	B	22	F	3	5	2	4	4	5	4	4	A	B	120	180
7	A	65	F	1	1	3	1	4	2	1	5	D	B	0	0
8	B	40	F	2	1	1	4	4	7	1	7	B	B	60	60
9	A	23	M	5	2	1	2	1	6	6	5	C	B	30	50 - 60
10	B	53	M	4	4	4	6	6	6	4	7	B	B	120	120
11	A	45	F	6	4	3	5	5	6	4	5	A	B	60	120
12	B	20	M	7	4	3	7	4	6	5	4	B	B	180	120
13	PAIRS	23	F	6	4	2	7	7	7	5	6	A	B	300	600
14	PAIRS	20	F	5	7	1	6	7	7	5	1	A	B	120	360
15	PAIRS	26	M	3	5	4	6	5	4	5	4	A	B	60	180
16	PAIRS	21	F	6	4	4	3	7	5		5	B	B	120	180 - 360
17	PAIRS	31	F	2	2	1	6	2	7	1	4	B	B	0	0
18	PAIRS			4	4	3	2	2	6	1	1	B	B	120	240 - 300
19	PAIRS	20	M	5	6	2	7	6	7	7	4	B	B	30	300
20	PAIRS	21	M	1	1	1	1	1	1	1	1	A	A	0	0
17	INSTR	23	M	4	7	5	4	1	6	1	7	A	B	180	60
18	INSTR			5	3	3	4	5	6	5	4	C	B	60	120

Q 1: How many times during the previous year have you visited an art gallery/ museum? (tick as appropriate)
A: None
B: 1 - 5
C: 5 - 10
D: More than 10

Q 2: How many different sounds could you identify while interacting with the painting? (tick as appropriate)
A: 1
B: 2 - 5
C: 5 - 10
D: More than 10

Q 3: How long do you think you could explore the painting before it would become boring?

1) Endurability: 1, 5, 8
2) Focused attentions: 3, 6, 7
3) Usability: 2, 4

Questionnaire, EXPERIMENT 2

Subject	Group	Age	Sex	1	2	3	4	5	6	7	Question 1 (A,B,C,D)	Question 2 (A,B,C,D)	Question 3 Alone (Minutes)	Question 3 In a group (Minutes)
1	A	48	M	7	4	7	4		4	7	B	C	3	0
2	B	21	F	6	6	5	7	6	5	6	D	D	3	5
3	B	23	F	7	5	5	7	7	7	2	A	B	5	10
4	B	54	F	5	6	7	7	5	2	7	B	C	10	6
5	B	23	M	5	7	5	7	6	4	7	A	C	7 weeks (?)	3 days (?)
6	B	19	M	7	2	4	6	5	3	6	A	D	2	4
7	B	20	M	6	7	7	6	7	4	7	B	C	10	20
8	A	20	M	7	7	5	6	6	6	7	B	B	10	0
9	A	20	M	5	6	5	7	6	7	7	A	C	5	10
10	A	20	M	5	4	7	6	4	7	4	A	B	0	0
11	A	23	M	4	5	7	4	1	3	7	D	B	5 - 10	5
12	A	22	F	5	4	4	5	1	2	3	B	B	5	8
13	B	26	M	7	5	7	4	5	2	7	B	C	3 - 5	15
14	B	30	F	5	5	7	6	6	6	3	D	B	0.5	1
15	B	19	M	7	5	7	4	3	4	2	B	B	1 - 2	1
16	B	19	F	4	4	6	6	4	6	4	A	C	5	10
17	B	19	M	7	7	6	7	6	7	6	A	C	5	10
18	B	18	M	7	7	7	5	6	7	6	A	C	2	5
19	B	20	M	5	5	7	3	3	5	4	A	D	2 - 3	5 - 10
20	B	21	M	3	3	6	3	4	5	4	A	C	2	5
21	A	52	M	3	6	4	6		3	1	B	C	2 - 3	5 - 6
22	A	22	F	7	5	7	6		3	5	C	B	3	7
23	A	54	F	1	4	6	6		1		C	B	5	0
24	A	31	M	7	7	7	7	5	5	7	C	C	2	5
25	A	22	M	7	4	3	4	1	1	6	C	C	2	6
26	A			7	4	5	4	6	6	5	A	B	0	0

Q 1: How many times during the previous year have you visited an art gallery/ museum? (tick as appropriate)
A: None
B: 1 - 5
C: 5 - 10
D: More than 10

Q 2: How many different sounds could you identify while interacting with the painting? (tick as appropriate)
A: 1
B: 2 - 4
C: 4 - 6
D: More than 6

Q 3: How long do you think you could explore the painting before it would become boring?

1) Endurability: 1, 4, 7
2) Focused attentions: 5, 6
3) Usability: 2, 3

Subject	Group	Age	Sex	Questionnaire, EXPERIMENT 1		Q 4: Do you have any suggestions or recommendations for future trials?
				Question 4		
1	A	28	M	I really didn't understand the purpose of the interaction if a clear description of how it works might be better. Still the exciting at the same time not knowing what it does		
2	B	21	M	None until I try the experiment again		
3	A	24	M			
4	B	20	M	Maybe use of 2 different pictures for only touch and touch + sound for better comparison		
5	A	23	M			
6	B	22	F	Keep up the good work		
7	A	65	F	Did not experience anything. The sound made the experience slightly more interesting because the paiting was boring. Use differently defined levels of visual simulation		
8	B	40	F	I didn't feel anything during the trial without sound. I only felt sound change with the sonic trial but gave me no interpretation of the texture or depth of the painting		
9	A	23	M	I would like the device/ ball like to move smother		
10	B	53	M			
11	A	45	F	Haptic feedback could be more obvious to create feedback pattern in my head		
12	B	20	M	Less sound, slightly overpowering and distracting		
13	PAIRS	23	F	I wasn't sure what was suppose to happen with the painting so maybe this can be explain more		
14	PAIRS	20	F			
15	PAIRS	26	M	Some people maybe won't understand the 3D space so an introduction into the device at a gallery could be useful		
16	PAIRS	21	F			
17	PAIRS	31	F			
18	PAIRS					
19	PAIRS	20	M			
20	PAIRS	21	M			
17	INSTR	23	M	Make visual manipulation with audio. That will capture the attention longer		
18	INSTR			If there were any animated/ projected visuals attached, it would be more fun to explore it		

Subject	Group	Age	Sex	Questionnaire, EXPERIMENT 2
				Question 4
1	A	48	M	Sense of wave motion of picture. Suggests this strongly
2	B	21	F	A bigger painting so that you can see I enjoy the movements and the sounds
3	B	23	F	Have a bigger picture
4	B	54	F	A more "professional" painting
5	B	23	M	
6	B	19	M	For the image to be interactive
7	B	20	M	
8	A	20	M	
9	A	20	M	
10	A	20	M	
11	A	23	M	"Touching" the painting is a great experience but personally I would like to know where I "was" on the painting
12	A	22	F	
13	B	26	M	Incentives
14	B	30	F	Add visual interactions too
15	B	19	M	More sounds, perhaps seagulls?
16	B	19	F	
17	B	19	M	Experimenting on more than one picture so the user could see and feel the difference
18	B	18	M	A painting including people maybe a public place with more sounds to explore. Maybe include smells
19	B	20	M	
20	B	21	M	
21	A	52	M	Needs more even split between above and below. Can't explore sky - A bit frustrating
22	A	22	F	A more detailed and more complicated picture
23	A	54	F	
24	A	31	M	Spherical art with trance tones as you go over "grooves" might be interesting, or even Australian art there
25	A	22	M	There is no reference where you are in the painting. No information about the painting. Too far to see the texture, the artistic skill of the paper.
26	A			

Protocol for "Cube-lifting Collaborative task" trial

Number of participants: 24

Number of questionnaires: 2 (one per experiment)

Trial estimated time per participant: 10 minutes

Logged data: Position (XYZ), Force (Newton) and Acceleration/Velocity (XYZ), Time, Stress/cognitive load responses, Videos from 4 cameras

Equipment:

- 2 PCs running Windows
- 2 Phantom Omni
- 4 Camcorders
- 2 Cubes with FSR sensors (4 sensors each cube).
- 2 GSR sensors

Inclusion criteria:

Healthy people who know how to operate a computer.

Participants with significant visual and cognitive impairments are excluded.

Study design:

At least 24 healthy participants will be recruited from Middlesex University to conduct an experiment that requires their engagement with a collaborative task. Participants will be divided into four equally numbered groups. Participating participants will together lift cubes and stack them on the top of each other in an unspecified order and following a specific sequence (e.g. lift cube A on top of cube B or cube B on top of cube A). Each group is involved in four different phases:

- Phase A: Participants manipulate the cubes together in the real world without talking to each other.

- Phase B: Participants manipulate the cubes in the real world and are encouraged to talk to each other.

- Phase C: Participants manipulate the cubes in the virtual world using the haptic device without talking to each other.

- Phase D: Participants manipulate the cubes in the virtual world using the haptic device and are encouraged to talk to each other.

For each of the four phases above, participants will perform the task three times. In addition, the order of the four phases will be randomised for each group (Group 1: ABCD; Group 2: CDAB; Group 3: DABC; Group 4: BCDA) to see if there are any differences in relation to quality of the interaction, kinematic features and psychophysiological responses (e.g. stress/cognitive load responses extracted from galvanic skin responses) related to the order of the phases. At the end of each experiment participants will be asked to fill a questionnaire survey rating the experience. The Minimum Torque-Change model will be used for the assessment of the quality of interactions i.e. the collected data will be plotted against different profiles (position, force, velocity and acceleration) generated by the model. The assumption is that performing an interactive task in a virtual environment via a network connection does not affect negatively the quality of movement, task engagement, motivation and skill attention of participants when compared to do the same task in the real world. Given that haptic interfaces have been developed to facilitate safe and natural interactions via the sense of touch, it is expected that a task carried out in the virtual world with haptic feedback can match or at least provide a close approximation to the same task in the real world. It is also assumed that the communication between participants plays a crucial role in the success of the task.

Outcome measures and data collection:

Participants will be assessed through a questionnaire using the Intrinsic Motivation Inventory (IMI), which has been used by (Colombo et al., 2007)

and (Mihelj et al., 2012). It consists of twenty-three statements divided into four scales: interest/enjoyment, perceived competence, effort/importance and pressure/tension. In addition kinematic data (positions, forces) from the participants' interaction will be collected using a tracking application created particularly for this experiment and FSR sensors while, stress levels data are recorded using GSR sensors. The success of collaborative task will be evaluated based on the minimization of error *(e)* and effort *(u),* which could be modeled as the minimization of the cost function (Jarrasse, Charalambous and Burdet, 2012).

1. Colombo R, Pisano F, Mazzone A, Delconte C, Micera S, Carrozza MC, Dario P, Minuco G: **Design strategies to improve patient motivation during robot-aided rehabilitation**. *J Neuroeng Rehabil* 2007, **4**(3).
2. Mihelj M, Novak D, Milavec M, Ziherl J, Olenšek A, Munih M: **Virtual rehabilitation environment using principles of intrinsic motivation and game design**. *Presence - Teleop Virt* 2012, **21**:1-15.
3. Jarrasse ́ N, Charalambous T, Burdet E (2012) A Framework to Describe, Analyze and Generate Interactive Motor Behaviors. PLoS ONE 7(11): e49945. doi:10.1371/journal.pone.0049945

Questionnaire

Participant No. ____ Group:__Age:____ Gender:____.

For each of the following statements, please indicate how true it is for you, using the following scale:

1	2	3	4	5	6	7
not at all			somewhat			very
true			true			true

9. I enjoyed doing this activity very much.	
10. I think I am pretty good at this activity.	
11. I put a lot of effort into this.	
12. I did not feel nervous at all while doing this.	
13. This activity was fun to do.	
14. I think I did pretty well at this activity, compared to other students.	
15. I didn't try very hard to do well at this activity.	
16. I felt very tense while doing this activity.	
17. I thought this was a boring activity.	
18. After working at this activity for a while, I felt pretty competent.	
19. I tried very hard on this activity.	
20. I was very relaxed in doing these.	
21. This activity did not hold my attention at all.	
22. I am satisfied with my performance at this task.	
23. It was important to me to do well at this task.	
24. I was anxious while working on this task.	

25. I would describe this activity as very interesting.	
26. I was pretty skilled at this activity.	
27. I didn't put much energy into this.	
28. I felt pressured while doing these.	
29. I thought this activity was quite enjoyable.	
30. This was an activity that I couldn't do very well.	
31. While I was doing this activity, I was thinking about how much I enjoyed it.	

Please tell us what you think of the experiment:

1. I found that I could manipulate the cubes easily in… (please tick ONE)

   ❐ The virtual environment

   ❐ The real environment

   ❐ Both environments

   ❐ None of the environments

2. I found that I could perform the tasks better while… (please tick ONE)
   ❐ Talking to the other participant
   ❐ Without talking to the other participant

3. What was your favourite phase?
   ❐ The real environment without talking   ❐ The real environment while talking
   ❐ The virtual environment without talking   ❐ The virtual environment while talking

   Why? _____

   _____

   _____

Thank you very much for taking your time to participate in this pilot study.

NOT TO BE SHOWN TO THE SUBJECT:

4) **Interest/Enjoyment: 1, 5, 9, 13, 17, 21, 23**

5) **Perceived Competence: 2, 6, 10, 14, 18, 22**

6) **Effort/Importance: 3, 7, 11, 15, 19**

7) **Pressure/Tension: 4, 8, 12, 16, 20**

Responses

Subject	Group	Age	Sex	Environm	Questionnaire																								Question 1	Question 2	Question 3
					Statements																								(A,B,C,D)	(A,B)	(A,B,C,D)
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23			
1	1		M	Virtual	4	3	6	4	4	3	2	5	3	4	5	2	1	3	4	6	4	3	2	5	4	6	4	B	A	A
				Real	6	6	5	6	6	5	6	2	3	6	4	4	1	5	5	4	4	4	4	4	5	1	5			
2	1	28	F	Virtual	7	6	6	7	7	5	1	1	1	1	1	7	1	6	7	1	7	6	4	1	7	2	7	B	A	C
				Real	7	5	7	7	7	5	1	1	1	1	4	7	1	5	6	1	7	6	6	1	7	1	7			
3	1		M	Virtual	7	5	4	6	7	4	2	1	1	2	4	4	1	6	7	2	7	4	1	4	7	4	7	B	A	C
				Real	4	7	1	7	4	6	4	1	4	6	1	7	6	6	4	1	1	6	4	1	4	1	2			
4	1		M	Virtual	7	2	7	6	7	3	1	2	1	4	7	5	1	5	7	2	7	3	1	2	7	3	1	B	A	D
				Real	7	5	6	5	7	2	1	2	1	7	7	5	1	6	7	3	7	4	2	1	7	2	1			
5	2		M	Virtual	6	7	7	6	7	7	5	2	2	6	3	6	1	7	7	2	6	7	4	2	6	1	4	C	B	C
				Real	6	6	3	6	6	7	5	2	2	6	2	6	2	7	7	2	6	6	4	1	6	1	3			
6	2	33	M	Virtual	7	7	3	6	7	7	1	2	1	7	6	4	1	7	5	1	4	7	6	5	6	1	4	C	A	D
				Real	7	7	4	4	6	7	1	4	3	7	6	4	2	7	6	4	5	7	6	5	6	1	4			
7	3	23	F	Virtual	7	3	6	3	6	3	3	1	1	4	5	3	2	4	4	2	6	4	2	1	5	3	5	C	A	D
				Real	5	4	5	3	5	3	1	2	2	4	5	3	2	5	4	3	3	4	2	2	4	3	3			
8	3	22	F	Virtual	6	3	5	4	7	2	3	4	1	2	4	2	1	3	5	6	7	1	1	4	7	3	5	B	A	C
				Real	5	5	5	3	6	4	2	3	2	4	4	2	1	4	4	5	6	1	1	4	6	3	5			
9	4	37	F	Virtual	5	3	4	5	6	4	7	6	1	3	5	4	2	1	6	5	5	2	3	2	5	5	5	B	A	D
				Real	6	6	5	4	4	3	3	3	2	3	3	5	3	3	3	2	4	3	3	1	5	4	4			
10	4		M	Virtual	6	3	7	5	6	4	1	7	1	4	7	5	2	5	7	6	7	3	6	4	7	6	5	B	A	B
				Real	7	4	7	6	7	5	1	4	1	5	7	5	1	5	7	3	7	5	6	5	7	4	7			
11	2	23	F	Virtual	7	6	5	7	6	4	5	1	1	5	3	6	1	6	5	1	6	5	4	1	6	2	6	C	B	C
				Real	6	7	3	6	6	5	2	2	2	6	5	5	1	6	6	2	6	6	6	2	6	2	6			
12	2	28	M	Virtual	6	3	4	4	6	1	4	4	2	3	4	4	3	1	3	4	6	1	4	4	6	7	4	D	B	C
				Real	6	1	3	3	5	1	4	4	2	1	4	4	3	1	4	3	6	1	4	4	6	7	4			
13	3	29	M	Virtual	4	5	5	7	7	5	1	1	1	5	5	6	2	5	4	3	5	5	3	3	5	3	2	B	A	D
				Real	6	6	3	7	7	5	1	1	1	5	5	6	2	5	4	3	5	5	3	3	5	3	2			
14	3	35	M	Virtual	6	5	2	6	6	4	6	1	1	6	2	6	1	5	2	2	4	4	6	2	6	2	2	B	A	D
				Real	5	5	2	6	5	4	6	1	1	6	2	6	1	6	2	2	4	4	6	2	5	2	2			
15	4	22	M	Virtual	7	4	7	5	6	4	2	4	1	5	6	4	1	5	4	4	7	5	3	1	7	5	4	B	B	C
				Real	7	6	4	5	7	6	2	3	1	7	5	4	2	6	2	3	6	6	5	1	7	2	4			
16	4	26	F	Virtual	7	5	6	6	7	6	1	1	1	6	6	6	1	6	6	1	7	6	1	1	6	1	6	B	A	C
				Real	6	6	6	6	6	4	1	1	1	6	6	6	1	6	6	1	5	5	1	1	6	1	5			
17	1	16	M	Virtual	5	4	6	5	5	4	1	5	1	4	5	5	3	6	5	5	6	2	1	5	6	2	3	B	A	B
				Real	4	2	6	4	6	1	1	3	2	1	7	3	1	5	6	3	5	4	1	6	6	5	2			
18	1	30	M	Virtual	6	3	7	6	6	2	1	1	1	4	7	3	1	2	7	2	6	2	2	1	6	6	6	D	A	D
				Real	5	5	7	6	7	4	1	5	1	4	6	3	2	2	7	2	3	3	2	1	6	5	6			
19	2	22	M	Virtual	7	6	3	6	7	4	4	2	1	4	2	6	1	6	5	2	6	5	4	1	6	2	3	C	A	D
				Real	6	4	5	7	7	5	3	2	1	3	3	5	1	6	4	2	7	5	2	1	6	2	1			
20	2	33	M	Virtual	7	3	5	7	7	3	1	4	1	4	6	4	1	4	4	3	7	3	1	3	7	4	4	B	A	D
				Real	5	6	6	5	5	5	1	4	3	5	6	4	3	6	4	3	5	5	2	3	6	2	3			
21	3	27	F	Virtual	6	4	6	6	6	4	4	2	2	5	6	6	2	3	6	3	6	3	5	3	6	4	5	B	A	D
				Real	6	6	4	6	6	5	6	3	2	6	5	3	3	6	6	3	6	6	6	2	7	3	5			
22	3	30	M	Virtual	6	4	6	7	7	2	1	1	4	2	7	6	4	3	6	1	3	2	2	3	4	5	4	B	A	B
				Real	6	5	6	7	4	2	1	1	4	5	7	7	4	5	7	1	4	3	1	2	4	4	3			
23	4	20	M	Virtual	7	2	6	3	6	2	2	4	1	5	6	3	1	3	4	3	5	2	2	4	6	4	4	B	A	D
				Real	4	5	4	5	4	3	4	3	5	5	3	4	5	5	3	3	3	4	4	3	3	4	3			
24	4	17	F	Virtual	7	3	5	2	6	4	1	3	1	5	6	7	1	4	4	5	7	2	3	1	7	3	6	B	A	C
				Real	7	7	3	5	6	7	3	1	1	6	3	5	2	7	4	3	7	6	4	1	6	1	7			

Subject	Group	Age	Sex	Questionnaire
				Question 3
1	1		M	Because we performed so well in the real task and it was even more rewarding when we did it without speaking like we could read each other's minds. It was a good experience
2	1	28	F	It was difficult to do it, so it made it more fun to succeed
3	1		M	It was hilarious how badly it went. The task was much harder
4	1		M	Was very much a challenge in the virtual environment, and I like a challenge
5	2		M	I enjoyed the challenge of co-operating without communicating. It felt satisfying to complete this well despite the challenge
6	2	33	M	Because of the novelty of the fact that we could manipulate an object in virtual reality while feeling the feedback and using verbal instructions, cues and communication to accomplish the task better/ faster
7	3	23	F	It was fun
8	3	22	F	Because it was funny how we wouldn't get it right without talking and virtual environment was more fun
9	4	37	F	It was very different to the real world activity
10	4		M	The task was easy to co-ordinate with my partner because we could collaborate more effectively
11	2	23	F	Experiencing moving a virtual object with another person
12	2	28	M	Stimulating on the screen + we were able to concentrate better when not talking
13	3	29	M	More fun because the cubes could fall easier
14	3	35	M	You could request less or more pressure and direct each other
15	4	22	M	It was more challenging and I felt because of that, it intrigued me more
16	4	26	F	Was harder to know what the other person was doing. Made it more challenging
17	1	16	M	Easier
18	1	30	M	It was fun, something a bit different. We completed the task but had a laugh at the same time!
19	2	22	M	There was a moment panic when we about lost control but we did it in the end
20	2	33	M	Good fun to try the task, easier with communication
21	3	27	F	A bit difficult task but it is very interesting when you can complete the task
22	3	30	M	More control and no delay(s)
23	4	20	M	Interaction with another participant while also using a virtual interface made task exciting/ enjoyable
24	4	17	F	I felt that even though it was the hardest phase, it was a good challenge that made the task not boring and

Appendix B: Video Codes

B1. Investigation on the difference of user's interactions with haptic/audio feedback while they are on their own or in a group: A study with healthy participants

Through this research, we are exploring the benefits of replacing the common *'virtual environment and haptic'* combination with a *'static painting, haptic and sound'* combination.

This encourages the user to develop his/her analytic skills, imagination, brain spacial skills and develop his/her touch and hearing senses.

These increased skills can be beneficial for rehabilitation.

Benefits of the *'static painting, haptic and sound'* combination

Analytic skills

Ref:

E2S7(21 on video Best Single)2.m4v

Experiment 2: Group 1 (single)

Subject 21 - This subject was looking for more details in the painting, he was exploring very carefully. User comment: 'Needs more even split between above and below. Can't explore sky - A bit frustrating

Certain profiles were analyzing the painting in details and were trying to match it with the haptic and sonic feedback.

Conclusion: We can see that some subjects look carefully at the painting and try to match visual details with the haptic feedback and sound cues. The subjects challenge the limitations and boundaries of the haptic feedback and sound cues in relation to the static visual (painting).

Imagination development

Experiment 2: Group 1 (single)

Subject 23 - including video footage after the questionnaire was filled in.

The participant expressed in great detail her emotional attachment to the sounds and the painting, referencing her childhood experience. The more she became engrossed in her own world, the more she stopped looking at the painting and was interacting with the haptic device and the sounds.

Conclusion: When the subjects finish with the analytic part and detach their attention from the painting, their next stage is focusing on the haptic feedback and sound cues, imagining their own visual/virtual environment.

We found that subjects moved between varying degrees back and forth of analytic and imagination

Spatial skills

E2S7(21 on video Best Single)1.m4v

E1S10(Best).m4v

Conclusion: When we present the subjects with a 2D image (static painting), they explore the painting using the haptic feedback and sonic cues as if it's a 3D environment.

We can see the subjects mapping the 2D reference with the haptic device, exploring the boundaries first. Doing so, they seem to

create a 3D environment in their brain matching the virtual environment.

They map the left and right borders of the painting with the left and right boundaries of the haptic workspace.

They map the virtual height and depth of the painting with the physical boundaries of the haptic workspace.

They then explore the space between these boundaries.

We noticed different levels of aptitude to this skill. Some explore freely, some for example get stuck at the bottom of the painting/under the ball (Experiment 1).

Touch and hearing senses

Ref:

eg E1S3

E1S10(Best).m4v

Conclusion: The sound clearly enhances the haptic experience.

When the subject feels, for example, their hand going into the water (Experiment 2), they experience haptic feedback with direct correlation to the sound (splashing). The sound is also directional, for example, move hand to the left, splash sound to the left.

The subject notices that the faster the movement of the hand, the haptic feedback increases, so does the intensity of the sound of the splash. This relates to many different elements of the paintings.

There is an increase in activity from the subject when the haptic feedback and sound cues match the virtual 3D environment with the 2D painting.

In Experiment 1, we notice that subjects are carefully exploring the environment using the haptic device

In Experiment 2, we notice subjects are freer with the exploration

As predicted, with painting in experiment 1 (ball painting) people were more cautious than those in experiment 2, but perhaps this is due to experiment 1 promoting shape determination and experiment 2 a more explorative behaviour. It would be good to do a more thorough analysis on the individual trajectories, but for this paper we have run out of time.

the benefit of groups

Ref:

E2S15_16(6_7 on video Best Pair).m4v

E2S17_18(13_14 on video).m4v

B2. Soundscape and Haptic Cues in an Interactive Painting: a Study with Autistic Children

Benefits of the *'static painting, haptic and sound'* combination

Analytic skills

Video: S1.m4v, S2.m4v, S3.m4v, S4.m4v, S5.m4v, S6.m4v, S7.m4v

Subject 1 - while subject 1 seemed active, he took his time and moved carefully

Subject 2, looked more interested in the device than the painting making more ballistic movements associated in particular with the water splashing sound (device hitting the water) and the wind sound above the water

Subject 3, 4, 5 and 6 showed a positive reaction towards the device and the painting, but were quieter and explorative

Subject 7 was more interested in all the aspects of the experience, exploring the painting gently but inquisitive as to where the sound of the water and touch sensation came from.

Conclusion: The results show that subjects' movements are varied and some subjects seem to be more explorative than the others (subject 1, 6&7).

Imagination development

Video: S7.m4v, S1&2.m4v

Subject 7 was looking and then running around the room to find out where the sound came from.

Subject 2 used the device while making circular motions and one can assume this related to imagining stirring (mixing) the sea because he could actually hear the sound corresponding to his action.

Conclusion: It is interesting to see how the sound effect contributed to the way the children interacted with the artefact. In fact, humans in general, have the tendency to use their imagination while interacting with good sound effects

Spatial skills

All videos

Some participants seemed to be more explorative than the others, they moved in various ways to explore different sound and haptic feedback.

Conclusion: This finding might indicate that adding more sound and haptic feedback could result in longer exploration and engagement with the installation.

Touch and hearing senses

Video: S2.m4v, S3.m4v

Subject 2 spent almost all of his time moving over the water because he seemed to like the water splash and windy sound while subject 3 on the other hand, liked the underwater sound.

Conclusion: Children interacted with the painting differently depending on their imagination and which sound they preferred

Communication skills

Video: S1&2, S3&4.m4v, S56&7.m4v

When participants explored in a group (or pairs), they had to 'negotiate' with each other and take turns to use the device.

Conclusion: It rises the opportunity to apply this type of interaction for social skills development which is important in human cognitive development especially for children with autism.

Appendix C: Samples of kinematic data

For all studies in chapter 6: data has been recorded at the frequency of 40Hz (maximum the PC can handle at that time). Note: Hit flag means 1 when user hits the 3D object, 0 when not hitting.

X	Y	Z	Velocity	Hit Flag	Time
0.004783	-0.81361	-0.56837	0.009887	1	0
0.004782	-0.81378	-0.56788	0.009784	1	0.0025
0.004785	-0.81329	-0.56805	0.009611	1	0.005
0.004785	-0.81329	-0.56805	0.00398	1	0.0075
0.004784	-0.81346	-0.56756	0.003937	1	0.01
0.004784	-0.81346	-0.56756	0.004355	1	0.0125
0.004784	-0.81346	-0.56756	0.003994	1	0.015
0.004784	-0.81346	-0.56756	0	1	0.0175
0.004784	-0.81346	-0.56756	0	1	0.02
0.004784	-0.81346	-0.56756	0	1	0.0225
0.004784	-0.81346	-0.56756	0	1	0.025
0.004784	-0.81346	-0.56756	0	1	0.0275
0.004784	-0.81346	-0.56756	0	1	0.03
0.004784	-0.81346	-0.56756	0	1	0.0325
0.004784	-0.81346	-0.56756	0	1	0.035
0.005102	-0.81346	-0.56756	0.00236	1	0.0375
0.005102	-0.81346	-0.56756	0.002359	1	0.04
0.005102	-0.81346	-0.56756	0.003077	1	0.0425
0.005102	-0.81346	-0.56756	0.002395	1	0.045
0.005102	-0.81346	-0.56756	0	1	0.0475

Appendix D: Ethical Forms

Cube-lifting Collaborative task - Information Sheet for Participants

Researchers: Mr Hoang Ha Le, Dr Rui Loureiro, Prof Martin Loomes

School of Science and Technology, Middlesex University, The Burroughs, Hendon, London, NW4 4BT

You are being invited to take part in a research study. Before you decide to participate, it is important for you to understand why the research is being done and what it will involve. Please take your time to read the following information carefully, and discuss it with others if you wish. Please ask if there is anything that is not clear or if you would like more information. Take your time to decide whether or not you wish to take part. Participation in this research is entirely voluntary. You do not have to take part if you do not want to. If you do decide to take part, then you may withdraw at any time, and you do not need to give a reason for you leaving the research.

<u>What is the purpose of this research?</u>

The research is being conducted to assess how different environments and communication modalities affect the quality of interactions between humans.

<u>What will happen to me if I take part in this research?</u>

If you agree to participate in this research, then you will be invited to conduct a simple collaborative task, which is working together with another participant to stack cubes on the top of each other. This experiment will take you about 30 - 45 minutes (including completing a simple questionnaire at the end of the experiment). You will be required to participate in the following four phases:

- Phase A: You manipulate the cubes together with another participant in the real world without talking to each other.

- Phase B: You manipulate the cubes in the real world with another participant and you are encouraged to talk to each other.

- Phase C: You manipulate the cubes in the virtual world with another participant using the haptic device without talking to each other.

- Phase D: You manipulate the cubes in the virtual world with another participant using the haptic device and you are encouraged to talk to each other.

For each of the four phases above, you will perform the task three times. In addition, the order of the four phases will be randomised for each group

(Group 1: ABCD; Group 2: CDAB; Group 3: DABC; Group 4: BCDA). During the execution of the tasks, we will collect information such as the movements performed, galvanic skin response picked up by sensors placed on two fingers and video (with voices and faces) from camcorders. At the end of each experiment you will be asked to fill a questionnaire survey rating the experience.

What are the possible disadvantages and risks of taking part?

There are no obvious risks to taking part in this research and very unlikely you will feel any discomfort. For phases A and B you will be manipulating plastic cubes using a stick. For phases C and D you will be manipulating 'virtual cubes' on a computer using a small robot called 'Phantom Omni' in a similar way as one would when drawing a sketch using a pen or playing a computer game using a joystick. All data will be kept confidential and your identity anonymous.

Consent

You will be given a copy of this information sheet to take away with you and you will be asked to sign a consent form before taking part in the research.

What will happen to the information I provide?

The information and data we collect as part of this evaluation may be used for analysis and subsequent publication. All results of this experiment are anonymous and your name does not form part of the data. We will ensure appropriate audio-visual anonymisation methods are used before any results are presented as reposts and at conferences or other scientific meetings. We will record video from the interaction between you and the other participant you will engage with (e.g. faces, hand movements and voices). We will use this information to help us identify certain communication determinants for interaction modeling. Your face will be pixelated and your voice will be transformed to hide your identity. Any copies of the video containing identifiable participants will be destroyed.

Who has reviewed the study?

All proposals for research using human participants are reviewed by an Ethics Committee before they can proceed. The Middlesex Computing Science Research Ethics Committee has reviewed this proposal.

Thank you for taking the time to read through this form. If you hav[e]
further questions about the research, please feel free to conta[ct]
research team directly.

CONSENT FORM

Participant Identification Number:

Title of Project: Cube-lifting Collaborative task

Researchers: Mr Hoang Ha Le, Dr Rui Loureiro, Prof Martin Loomes

1. I confirm that I have read and understood the information sheet dated ....……………..…for the above study and have had the opportunity to ask questions.

2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason.

3. I agree that this form that bears my signature may be seen by a designated auditor.

4. I agree that my non-identifiable research data may be stored in National Archives and be used anonymously by others for future research. I am assured that the confidentiality of my personal data will be upheld through the removal of any identifiers.

5. I agree to take part in the above study.

_____   _____

Date   Signature

A copy of this consent form has been given to you to keep for your records and reference.

DEBRIEFING SHEET

Cube-lifting Collaborative task

Researchers: Mr Hoang Ha Le, Dr Rui Loureiro, Prof Martin Loomes

School of Science and Technology, Middlesex University, The Burroughs, Hendon, London, NW4 4BT

Thank you for taking part in this research today.

When the experiment is complete, we will analyse the data using a mixture of research techniques.

Do you have any additional questions for me about the research process or what will happen to this information?

If you have any questions about this research or the findings, then do please get in touch with us using the details at the top of this sheet.

*Please read the **MU Code of Practice for Research: Principles and Procedures[i]**. The purpose of this form is to help staff and students in their pursuit of ethical research methodologies and procedures. Students should complete this form in consultation with their supervisors. The **supervisor is responsible for submission[ii]** of this form and required accompanying documents[iii]. **No fieldwork should begin until your Research Ethics Committee (REC) has given approval**.*

Middlesex University Research Ethics Review Form A

Section 1 – Applicant details

1.1 Details of Principal Investigator/Supervisor[iv]		
1.1a Name: Rui Loureiro	1.1b Department/Position: Design Engineering and Mathematics/ Visiting Professor	
1.1c Qualifications: BEng (Hons), MSc, PhD	1.1d Email:R.Loureiro@mdx.ac.uk	1.1e Tel:
1.2 Details of Student Researcher (if applicable)		
1.2a Name: Hoang Ha Le	1.2b Programme of study/module: Doctoral programme	
1.2c Qualifications: BSc (Hons), MSc	1.2d Email: H.Le@mdx.ac.uk	1.2e Tel:
1.3 Details of any co-investigators (if applicable)		
1.3a Name: Prof. Martin Loomes	1.3b Organisation: Middlesex Univ	1.3c Email: M.Loomes@mdx.ac.uk
1.3d Name:	1.3e Organisation:	1.3f Email:
1.3g Name:	1.3h Organisation:	1.3i Email:
1.4 Details of External Funding		

Section 2 – Details of proposed study

2.1 Research project title	Cube-lifting Collaborative task		
2.2 Proposed start date	19/01/2015	2.3 Proposed end date	30/03/2015
2.4 Main aims of the study			
This study is a part of Mr. Hoang Ha Le's PhD research. The purpose of this study is to investigate how different environments and communication modalities affect the quality of interactions between humans			
2.5 Details of study design, data collection methods (e.g., interviews, questionnaire, observation etc.) and/or secondary data sources (e.g., UK National Statistics) to be used in the research			

Study design:

At least 16 healthy participants will be recruited to conduct an experiment that requires their engagement with a collaborative task. Participants will be divided into four equally numbered groups. Participating participants will together lift cubes and stack them on the top of each other in an unspecified order and following a specific sequence (e.g. lift cube A on top of cube B or cube B on top of cube A). Each group is involved in four different phases:

- Phase A: Participants manipulate the cubes together in the real world without talking to each other.

- Phase B: Participants manipulate the cubes in the real world and are encouraged to talk to each other.

- Phase C: Participants manipulate the cubes in the virtual world using the haptic device without talking to each other.

- Phase D: Participants manipulate the cubes in the virtual world using the haptic device and are encouraged to talk to each other.

For each of the four phases above, participants will perform the task three times. In addition, the order of the four phases will be randomised for each group (Group 1: ABCD; Group 2: CDAB; Group 3: DABC; Group 4: BCDA) to see if there are any differences in relation to quality of the interaction, kinematic features and psychophysiological responses (e.g. stress/cognitive load responses extracted from galvanic skin responses) related to the order of the phases. At the end of each experiment participants will be asked to fill a questionnaire survey rating the experience. An optimal model will be used for the assessment of the quality of interactions i.e. the collected data will be plotted against different profiles (position, force, velocity and acceleration) generated by the model. The assumption is that performing an interactive task in a virtual environment via a network connection does not affect negatively the quality of movement, task engagement, motivation and skill attention of participants when compared to do the same task in the real world. Given that haptic interfaces have been developed to facilitate safe and natural interactions via the sense of touch, it is expected that a task carried out in the virtual world with haptic feedback can match or at least provide a close approximation to the same task in the real world. It is also assumed that the communication between participants plays a crucial role in the success of the task.

Outcome measures and data collection:

Participants will be assessed through a questionnaire using the Intrinsic Motivation Inventory (IMI), which has been used by (Colombo et al., 2007; Johnson et al., 2008; Mihelj et al., 2012). It consists of twenty-three statements divided into four scales: interest/enjoyment, perceived competence, effort/importance and pressure/tension. In addition kinematic data (positions, forces) from the participants' interaction will be collected using a tracking application created particularly for this experiment and FSR sensors while, stress levels data are recorded using GSR sensors. The success of collaborative task will be evaluated based on the minimization of

error *(e)* and effort *(u),* which could be modeled as the minimization of the cost function (Jarrasse, Charalambous and Burdet, 2012).

4. Colombo R, Pisano F, Mazzone A, Delconte C, Micera S, Carrozza MC, Dario P, Minuco G: **Design strategies to improve patient motivation during robot-aided rehabilitation**. *J Neuroeng Rehabil* 2007, **4**(3).
5. Johnson, M.J., Loureiro, R.C.V., and Harwin, W.S. (2008). **Collaborative Tele-rehabilitation and Robot-Mediated Therapy for Stroke Rehabilitation at Home or Clinic**. Journal of Intelligent Service Robotics, Springer Berlin, 1(2): 109-121.
6. Mihelj M, Novak D, Milavec M, Ziherl J, Olenšek A, Munih M: **Virtual rehabilitation environment using principles of intrinsic motivation and game design**. *Presence - Teleop Virt* 2012, **21**:1-15.
7. Jarrasse ´ N, Charalambous T, Burdet E (2012) A Framework to Describe, Analyze and Generate Interactive Motor Behaviors. PLoS ONE 7(11): e49945. doi:10.1371/journal.pone.0049945

Section 3 – Initial Checklist to be completed by ALL applicants

Indicate your response

3.1 The research[v] **DOES NOT involve human participants**[vi] or **animals** (or **animal by-products**)[vii] or any activity that might **cause damage** e.g., to the **environment or precious artefacts** i.e., the research involves **analytical** or **simulation modelling,** or is a **literary**, **historical or theoretical project** relying on sources available in the **public domain**[viii] and **does not** make use of **personal** or **personal sensitive data**.	Agree	Disagree
3.2 The research involves **secondary data analysis**[ix] where the researcher can provide evidence that they have the necessary **approval to access*** the data *(*please provide evidence of approval)* and **DOES NOT involve** access to records of **personal or sensitive information** concerning **identifiable individuals**, or **research which may involve sharing of confidential information beyond the initial consent given**. *If there is data linkage or it may be otherwise possible to identify participants, please complete all sections of this form and* **the Data Protection Act Checklist for Researchers**.	Agree	Disagree
3.3 The research **already has ethical approval from another UK Ethics Committee*** (e.g., a UK HEI or organisation e.g., NHS, IRAS[x]) and the liability insurance is provided by the other body/institution[xi]. *(*Please provide evidence of ethics approval)*	Agree	Disagree
3.4 The **outputs from research** (e.g., products, guidelines, publications etc.) are **not likely to cause harm to others**, and are **in-line with UK legislation**[xii].	Agree	Disagree

If you have answered **AGREE** to statements 3.1 or 3.2 or 3.3, and in all cases 3.4, please complete **Section 8** and **sign the declaration in Section 9. Otherwise, please complete the remainder of this form UNLESS your research involves Human Tissue (including blood)**[xiii] **then please complete the Natural Sciences REC form**[xiv] **or involves psychological research and requires approval from the Psychology REC and completion of the Psychology REC form.**

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[i] ***MU Code of Practice for Research: Principles and Procedures*** *is available on the MU intranet and internet*

[ii] *See list of* ***Research Ethics Committee Contacts List*** *on the intranet and internet for submission process details*

[iii] ***Required accompanying documents*** *include the following:*
1. *Participant information sheet*
2. *Informed consent sheet*
3. *Debriefing information*

4. Risk assessment form (required if research is to be conducted away from MU property. Institutions/locations listed for data collection must match original letters of acceptance.)

[iv] Please note that a student (UG, PG taught or research) cannot be the Principal Investigator for ethics purposes

[v] Refer to **Middlesex University: Definition of Research**

[vi] **Human participants** are defined as including living human beings, human beings who have recently died (cadavers, human remains and body parts), embryos and foetuses, human tissue ad bodily fluids, and human data and records (such as, but not restricted to medical, genetic, financial, personal, criminal or administrative records and test results including scholastic achievements). All data collection involving human participants and/or personal data and/or sensitive personal data must receive ethics approval prior to the research commencing, with the exception of the following, which are not considered 'research': a) routine audit, b) performance reviews, c) quality assurance studies, d) testing within normal education requirements, e) literary or artistic criticism. Ref: ESRC (FRE, 2012).

[vii] The **Middlesex University Statement on the Use of Animals in Research, Teaching and Practice** is available on the intranet and internet

[viii] Sources available in the public domain include published biographies, newspaper accounts, published minutes of meetings.

[ix] Refer to **Middlesex University: Definition of Research** section on secondary data analysis.

[x] The **Integrated Research Application System** (IRAS) will be applicable to research in the Confidentiality Advisory Group (CAG), National Offender Management Service (NOMS), NHS, and other health and social care / community care research review bodies in the UK. See https://www.myresearchproject.org.uk for accessing the IRAS system.

[xi] If **MU liability sponsorship** is required please complete all sections of this form

[xii] For example under the **Computer Misuse Act** (1990) and the **Data Protection Act** (1998)

[xiii] **Human Tissue** (under the Human Tissue Act, 2004) refers to 'relevant material' that contains at least a single cell from a human body, e.g., organs, blood, bodily waste products, cell deposits or tissue sections. (It does not include embryos outside the human body or hair and nail from the body of a living person.) Please refer to the HTA list of relevant materials at http://www.hta.gov.uk/legislationpoliciesandcodesofpractice/definitiono frelevantmaterial/listofmaterialsconsideredtoberelevantmaterialunderthe humantissueact2004.cfm

[xiv] For research involving **Human Tissue (including blood etc.)** please use the form and process for the Natural Sciences Department. For **psychological research** please use the forms and process for the Psychology Department.

Section 4 – Research data sources and participants

Indicate your response

4.1 Secondary data research *(e.g., published data, archives, court reports, hospital records, case notes, internet site etc.)* Please **specify data set** to be used and **how it will be obtained** and whether appropriate or required **permission** will be obtained:	N/A
4.2 Primary data from human participants: Please specify categories of human participants: *(e.g., students; those in an unequal relationship (e.g., your own students): general public; specific group(s) or team(s). (Note: NHS patients, and/or their relatives/carers, vulnerable adults unable to give informed consent must be reviewed by NHS NRES via the IRAS system. Collecting data from under-16yr olds and vulnerable adults will require DBS see 6.11)* *Middlesex University students, staff and general public.* i) **Categories and number** of participants: Healthy people, 16 participants ii) How will participants be **recruited and approached?** (e.g., using email, social media sites, posters, letters of introduction etc), what **contact/reply arrangements** will be made (e.g., mdx email or details a dedicated email account, or skype address for the research etc) or **accessed** gained to groups of participants (e.g., through gatekeepers, e.g., organisations, managers, parents, schools etc) *Please provide details: Participants will be approached via email or directly in person. The experiment will take place at Middlesex University's Hendon campus.* iii) Details of **materials** to be used/**resources** required for this study: *(Please provide copies of questionnaires, indicative interview questions, topic guide/prompts, visual images etc. to be used in this research)* *2 PCs running Windows, 2 Phantom Omni (Haptic devices), 4 Camcorders, 2 Cubes with FSR sensors (4 sensors each cube), 2 GSR sensors placed on participants' fingers.*	N/A

4.3 Animals or the use of animal by-products[xv]**:** If the research involves the participation and/or observation of animals or the use of animal by-products please refer to the *MU Statement on the Use of Animals in Research, Teaching and Practice* and provide the following details:
 	
    i)   Type of animal/animal by-product
    ii)   Justification for use of animal/animal by-products(s)
    iii)   Where data collection is being undertaken
    iv)   Where animals/animal by-products are kept and care/storage facilities/disposal[xvi]
    v)   Evidence of relevant licence/permissions (where applicable)
 	
N/A
	N/A

4.4 Other data sources to be collected/used not categorised above *e.g., flora/foliage, minerals, precious artefacts etc.* Please provide details:
 	
    i)   Type of data: Position (XYZ), Force (Newton) and Acceleration/Velocity (XYZ), Time, Stress/cognitive load responses, Video footage from cameras
    ii)   Justification for use: The collected data will be used to evaluate the quality of collaborative task. We need both the qualitative and quantitative data to understand the interaction aiding the development of a optimal model that takes into account both the physical and behavioural/social interactions.
	N/A

iii)	Where data collection is being undertaken: At Middlesex University			
iv)	Where the data will be kept and care/storage facilities: All data collected will be saved in a single limited access (password protected) computer. All written documentation held in secured filing cabinets. Access to the study data will be restricted to researchers only. After conclusion of the project data will be stored on CD ROM for 10 years. Original data will be removed from all hard drives. CD ROM and written data will be stored in a secure holding area by the PI.			
v)	Evidence of required licence/permissions (where applicable)			

Section 5 – Anonymity, confidentiality and consent for primary and secondary research   *Indicate your response*

	Yes	No	NA
5.1 Will the research involve collecting or analysing **personal data or sensitive personal data**? *(i.e., personal data refers to information that may identify individuals e.g., name, address, date of birth, opinion, specifc event, set of characteristics that would clearly identify individuals or very small groups. Sensitive personal data refers to racial or ethnic origin, political opinion, religious beliefs, trade union membership, sexual life, physical or mental health, criminal matters.)* *If 'yes', consider irreversibly anonymising data, if possible, by removing names and other linked or identifying information which may still identify an individual without their name. Alternatively, if personal or sensitive personal data is required for the research, you* **must comply with the Data Protection Act (DPA)(1998)** *and understand your responsibiiities under the DPA and have received* **data protection training**. *Please complete the* **Data Protection Act Checklist for Researchers** *All results of this experiment are anonymous and participants' name and identity does not form part of the data. Participants will be allocated a reference code for data analysis. Names and other details that may identify the participants will be removed.*	Yes	No	NA
5.2 Will lists of identity numbers/codes or pseudonyms for individuals and/or organisations (i.e., **linking keys to personal identifiers**) be stored securely and separately from the research data and destroyed after the study to avoid any risk of confidentiality being compromised? *If 'no' please provide details:*	Yes	No	NA
5.3 Will you tell participants that their data will be treated **confidentially** and the **limits of anonymity** will be made clear in your **Participant Information Sheet***? (e.g., their identities as participants will be concealed unless prior consent is given to include the name of the participant in any documents resulting from the research. Consider how participants' narratives, quotes or involvement in specific events may make anonymity difficult to maintain.) *Please provide details how you will ensure this: At the beginning of the experiment, the Participant Information Sheet will be handed to participants and they will be given enough time to read through it and ask questions.*	Yes	No	NA
5.4 Will you obtain **Written Informed Consent**[xvii]* directly from research participants (if applicable)? *If 'no' please provide details:* *If 'yes' please specify how and when this will be achieved:* *Consent form will be provided to the participants after they have read the Participant Information Sheet.*	Yes	No	NA
5.5 Will you obtain **Written Informed Consent*** directly from gatekeepers (if applicable)? *If 'no' please provide details:* *If 'yes' please specify how and when this will be achieved:*	Yes	No	NA

5.6 Will you inform participants that their participation is **voluntary** and that they have a **right to withdraw** from the research at any time? *If 'no' please provide details:*	Yes	No	NA
5.7 Will you have a process for managing **withdrawal of consent**? *Please provide details:* *Participants will be free to withdraw at any time and without giving a reason. On notification of withdrawal, any data collected will be destroyed.*	Yes	No	NA
5.8 Will it be necessary for **participants to take part in the study without their knowledge and consent** at the time, or by **deception** e.g., covert observation? *If 'yes', please provide justification and details of how this will be managed to respect the participants/third parties involved to respect their privacy, values and to minimise any risk of harmful consequences:*	Yes	No	NA
5.9 Will you provide a **<u>Written Debriefing Sheet</u>***? (if applicable)	Yes	No	NA
5.10 Will you need **consent from people** who appear **in visual data** (e.g., photos or films)? *If 'yes' please provide details:*	Yes	No	NA
5.11 Will you **audio or video record** interviews and/or observations? *If 'yes' please provide details on how **participants' anonymity** will be maintained:* *We will ensure appropriate audio-visual anonymisation methods (e.g. using a different name: replacing personal identifiers with other references; aggregation: displaying values as totals, so that none of the individual values which could identify an individual is shown; data reduction: removing values that are not required for the purpose) are used before any results are presented at conferences or other scientific meetings. In particular, we will ensure all participants' faces from photos and videos will be pixelated to hide their identities. Also, participants' voices will be de-identified using voice transformation software.*	Yes	No	NA
5.12 If the research involves **participants responding to internet surveys, emails, chatroom discussions, blogs, interactive games, social media and networking sites etc,** how will you obtain permission from the website authors, or informed consent from participants, and ensure anonymity and protect confidentiality in an environment that generates significant amounts of background information e.g., data logs, IP addresses, cookies and caches and/or with low levels of system security? *Please provide details:*	Yes	No	NA

Please **submit copies of these forms with this application*

Section 6 – Avoiding harm: risk assessment and management, safety and legal issues

6.1 Will you use an **experimental research design** (ie., implement a specific plan for assigning participants to conditions and noting consequent changes?)	Yes	No	NA

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	Yes	No	NA
If 'yes', please provide details of treatment/intervention (and specify is these are intrusive interventions e.g., hypnosis or physical exercise, or include the use of drugs, placebos or other substances e.g., vitamins, food substances etc.) and provide details of required resources for this study:			
6.2 Will the research involve **discussion of sensitive topics**? (e.g., sexual activity, drug use etc) *If 'yes' please provide details of how possible adverse reactions will be avoided and what support will be in place to manage any adverse consequences:*	Yes	No	NA
6.3 Is **pain or more than mild discomfort** likely to result from the study? *If 'yes' please provide details:*	Yes	No	NA
6.4 Could the study induce **psychological stress or anxiety** or **cause harm or negative consequences** beyond the risks encountered in normal life? *If 'yes' please provide details and state how participants will be supported:*	Yes	No	NA
6.5 Will the study involve prolonged and repetitive testing? *If 'yes' please provide details, justification and state how participants will be supported and length of each **data collection session**, number of sessions and location of data collection:*	Yes	No	NA
6.6 Will this research be conducted **off-site** (i.e., not on MU premises)? *If 'yes', please provide details of other locations and complete a Risk Assessment Form for Fieldwork[xviii] to be submitted with this form.* *If 'no', a risk assessment form will need to be completed if the research involves groups of participants and there is a need to control space risks or to comply with relevant licence(s).*	Yes	No	NA
6.7 Will you **be alone** with individual participants or group of participants place you at risk? *If 'yes' please state how this can be avoided or managed?*	Yes	No	NA
6.8 Are there any **adverse risks** or **safety issues** (e.g., from **potential hazards)** that your methodology raises for you and/or for your participants or others? *If 'yes', please specify and provide details of mitigating actions that will be taken* (e.g., travelling alone, working in hazardous conditions, discussing illegal activities on-line etc*.) and how you, and your participants/third parties will be supported?*	Yes	No	NA
6.9 Is the research or outputs from the research **likely to cause harm** to others (e.g., to their physical well-being, mental health, dignity or personal values) to an extent greater than that encountered in ordinary life? *Please provide details; e.g., dissemination plans and how an increased risk of harm will be avoided.*	Yes	No	NA

6.10 Is this research likely to have a **damaging effect on the environment e.g., damage to habitats, plants**, or **sites** of **archaeological** or **geological** or **cultural** significance? Or a **negative impact on people living/working in** the **immediate locality** of the study? *If 'yes' please provide details and state how damage will be minimised:*	Yes	No	NA
6.11 Will this research require a current **Disclosure and Barring Service** (DBS) Certificate*? **Needed when working with under-16yr olds and/or vulnerable adults for example, in education or healthcare contexts.*	Yes	No	NA

Section 7 – Research Sponsorship and/or Collaboration

7.1 Does the research have a **sponsor** (i.e., any person or organisation who provides support for the research in the form of income, use of data, facilities, materials, assistance with data collection etc) that may have **ethical implications for the research**? *If 'yes' please provide details of the role of the funder and issues:*	Yes	No
7.2 Does the research involve an **international collaborator** or research conducted **overseas**? *If 'yes', what ethical review procedures must this research comply with for that country, and what steps have been taken to comply with these: (e.g., Do you need local permission/approval? Are there any country specific cultural social or legal considerations that need to be taken into account? Who will be collecting the data overseas? Have you considered intellectual property issues?)*	Yes	No
7.3 Does this research require **Approval from an External Research Ethics Committee**? *(e.g., Some organisations, agencies and local authorities require this[xix] If 'yes' please provide details:*	Yes	No
7.4 Will this research or part of it be conducted in a language **other than English**? *If 'yes', full translations of all non-English materials will need to be submitted.*	Yes	No

Section 8 – Other Issues – to be completed by ALL applicants

8.1 Does the research involve any **ethical and/or legal issues not already covered** that should be taken into consideration? *If 'yes' please give details:*	Yes	No
8.2 Do you or your researchers require training on the requirements of the **Data Protection Act for researchers**?	Yes	No
8.3 Does the research raise **any other risks to safety for you or others** that would be greater than in normal life? *If 'yes' please complete the MU Risk Assessment Form for submission to the REC with this form.*	Yes	No
8.4 Will participants receive any **reimbursements or payments** for participating? *If 'yes' please provide details and justification:*	Yes	No

8.5 Are there any **conflicts of interests to be declared** in relation to this research?	Yes^{xx}	No

Section 9: Declaration – to be completed by ALL applicants

As principal investigator or student researcher I confirm that:

1. I have read and agree to abide by the relevant Code(s) of Ethics appropriate to my research field and topic.
2. I have reviewed the information provided in this form and believe it accurately represents the proposed research.
3. I have read and agree to abide by the University's *Code of Practice For Research: Principles and Procedures.*
4. I agree to inform my Supervisor/ Research Ethics Committee of any adverse effects or changes to the research procedures.
5. I understand that research/data may be subject to inspection for audit purposes and I agree to participate in any audit procedures required by the Research Ethics Committee (REC) if requested.
6. I understand that personal data about me contained in this form will be managed in accordance with the Data Protection Act.
7. I have completed and signed a risk assessment for this research study (if applicable).

Principal Investigator Name:...Rui Loureiro......................... **Signature:**.......................................**Date:** 07/01/2015

Student Name:.........Hoang Ha Le.................. ....**Signature:**.....................................**Date:** 07/01/2015

As supervisor I confirm that:

1. I have reviewed all the information submitted with this research ethics application and believe it accurately represents the proposed research.
2. I accept responsibility for guiding the applicant so as to ensure compliance with the terms of the protocol and with any applicable Code(s) of Ethics.
3. I understand that research/data may be subject to inspection for audit purposes and I agree to participate in any audit procedures required by the Research Ethics Committee (REC) if requested.
4. I confirm that it is my responsibility to ensure that students under my supervision undertake a risk assessment to ensure that health and safety of themselves, participants and others is not jeopardised during the course of this study.
5. I understand that personal data about me contained in this form will be managed in accordance with the Data Protection Act.
6. I have seen and signed a risk assessment for this research study (if applicable).

Supervisor's recommendation to the REC		
This is a low risk project and all ethical, legal and safety issues have been sufficiently addressed	Yes	No

Supervisor's Name:...........Rui Loureiro.........................**Signature:** ....**Date:** 07/01/2015

[xvii] *Researchers that intend to obtain* **consent from participants to use human tissue** *must attend a consent training course at MU as part of the HTA requirements. See the Natural Science REC info for further details.*

[xviii] *The* **Middlesex University Risk Assessment Form** *is available on the intranet and internet*

[xix] **External ethics approval** *is required from some organisations, agencies and local authorities that have their own ethics processes and require completion of additional ethical approval forms and processing in addition to the MU process. It is your responsibility to check whether additional permissions apply to you.*

[xx] *If 'yes' please complete the* **MU: Code of Practice for Research Appendix 2- Disclosure of Potential Conflict of Interest** *form for submission to the REC with this form.*

Please submit to your relevant Research Ethics Committee.

Please indicate which documents will be submitted

Please check and attach the following documents where applicable:			
1. Evidence of external approval – from external ethics body	Yes	No	NA
2. Evidence of external approval – for access to secondary data	Yes	No	NA
3. Letter of permission (if required from organisation where research is to be conducted)	Yes	No	NA
4. Participant Information Sheet	Yes	No	NA
5. Written Informed Consent Sheet	Yes	No	NA
6. Written Debriefing Sheet	Yes	No	NA
7. Completed Risk Assessment Form	Yes	No	NA
8. Copy of questionnaire/interview guide/details of materials for data collection (including translations, visual images etc.)	Yes	No	NA
9. Disclosure of Conflict of Interests (if applicable)	Yes	No	NA
10. Evidence of relevant licence for research with animals/animal by-products	Yes	No	NA

Examples of Consent Forms and Participant Information sheets can be found on the MU Ethics intranet site

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FOR RESEARCH ETHICS COMMITTEE (REC/RESC) USE ONLY   **REC no:**

Date:

Project title:

Reviewer's decision *(Please avoid revealing the reviewer's identity if possible)*		
1. Approved	Yes	No
2. Approved subject to the following:	Yes	No
3. Revisions and further information required:	Yes	No
4. Not Approved for the following reasons:	Yes	No

WHERE A SECOND REVIEWER IS REQUIRED:

Second reviewer's decision *(Please avoid revealing the reviewer's identity if possible)*		
1. Approved:	Yes	No
2. Approved subject to the following:	Yes	No
3. Revisions and further information required:	Yes	No
4. Not Approved for the following reasons:	Yes	No

Chair of REC/RESC or nominee Name:...**......Date**: ……………………..

Signature: ………………………………………………………………

NOTES FOR COMPLETING THIS FORM

State-of-the-Art Pointing Solutions for the OEM

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CERTIFIED

Version 1.0

90-45632 Rev. D

Force Sensing Resistors *An Overview of the Technology*

Force Sensing Resistors (FSR) are a polymer thick film (PTF) device which exhibits a decrease in resistance with an increase in the force applied to the active surface. Its force sensitivity is optimized for use in human touch control of electronic devices. FSRs are not a load cell or strain gauge, though they have similar properties. FSRs are not suitable for precision measurements.

FLEXIBLE SUBSTRATE WITH PRINTED SEMI-CONDUCTOR

SPACER ADHESIVE

SPACER OPENING

VENT

FLEXIBLE SUBSTRATE WITH PRINTED INTERDIGITATING ELECTRODES

ACTIVE AREA

TAIL

Force vs. Resistance
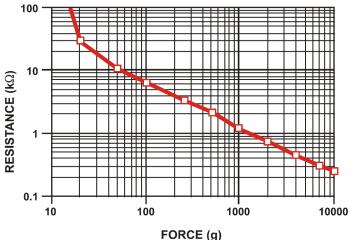
The force vs. resistance characteristic shown in Figure 2 provides an overview of FSR typical response behavior. For interpretational convenience, the force

vs. resistance data is plotted on a log/log   Figure 1: FSR Construction format. These data are representative of our typical devices, with this particular

force-resistance characteristic being the response of evaluation part # 402 (0.5" [12.7 mm] diameter circular active area). A stainless steel actuator with a 0.4" [10.0 mm] diameter hemispherical tip of 60 durometer polyurethane rubber was used to actuate the FSR device. In general, FSR response approximately follows an inverse power-law characteristic (roughly 1/R).

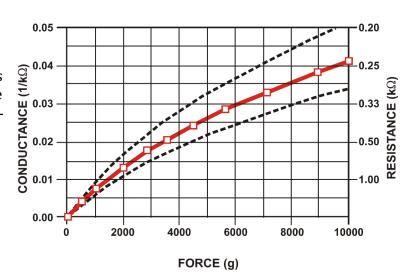Referring to Figure 2, at the low force end of the force-resistance characteristic, a switchlike response is evident. This turn-on threshold, or 'break force", that swings the resistance from greater than 100 kΩ to about

10 kΩ (the beginning of the dynamic range that follows a power-law) is determined by the substrate and overlay thickness and flexibility, size and shape of the actuator, and spacer-adhesive thickness (the gap between the facing conductive elements). Break force increases with increasing substrate and overlay rigidity, actuator size, and spaceradhesive thickness. Eliminating the adhesive, or keeping it well away from the area where the force is being applied, such as the center of a large FSR device, will give it a lower rest resistance (e.g. stand-off resistance).

Figure 2: Resistance vs. Force

At the high force end of the dynamic range, the response deviates from the power-law behavior, and eventually saturates to a point where increases in force yield little or no decrease in resistance. Under these conditions of Figure 2, this saturation force is beyond 10 kg. The saturation point is more a function of pressure than force. The saturation pressure of a typical FSR is on the order of 100 to 200 psi.
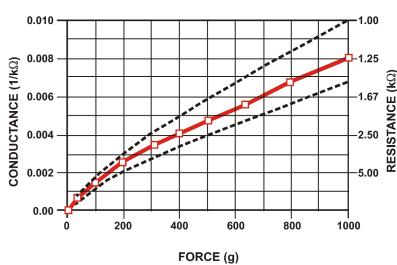
For the data shown in Figures 2, 3 and 4, the actual measured pressure range is 0 to 175 psi (0 to 22 lbs applied the saturation force can be measured by spreading the force over a greater over 0.125 in^2). Forces higher than

Figure 3:

area; the overall pressure is then kept Conductance vs. Force (0-10Kg) below the saturation point, and

dynamic response is maintained. However, the converse of this effect is also true, smaller actuators will saturate FSRs earlier in the dynamic range, since the saturation point is reached at a lower force.

Force vs. Conductance

In Figure 3, the conductance is plotted vs. force (the inverse of resistance: 1/r). This format allows interpretation on a linear scale. For reference, the corresponding resistance values are also included on the right vertical axis. A simple circuit called a current-to-voltage converter (see page 21) gives a voltage output directly proportional to FSR conductance and can be useful where response linearity is desired. Figure 3 also includes a typical part-to-part repeatability

Figure 4:
Conductance vs. Force (0-1Kg) Low Force Range

envelope. This error band determines the maximum accuracy of any general force measurement. The spread or width of the band is strongly dependent on the repeatability of any actuating and measuring system, as well as the repeatability tolerance held by Interlink Electronics during FSR production. Typically, the part-to-part repeatability tolerance held during manufacturing ranges from ± 15% to ± 25% of an established nominal resistance.

Figure 4 highlights the 0-1 kg (0-2.2 lbs) range of the conductance-force characteristic. As in Figure 3, the corresponding resistance values are included for reference. This range is common to human interface applications. Since the conductance response in this range is fairly linear, the force resolution will be uniform and data interpretation simplified. The typical part-to-part error band is also shown for this touch range. In most human touch control applications this error is insignificant, since human touch is fairly inaccurate. Human factors studies have shown that in this force range repeatability errors of less than ± 50% are difficult to discern by touch alone.

FSR Integration Notes *A Step-by-Step Guide to Optimal Use*

For best results, follow these seven steps when beginning any new product design, proof-of-concept, technology evaluation, or first prototype implementation:

1. Start with Reasonable Expectations (Know Your Sensor)

The FSR sensor is not a strain gauge, load cell or pressure transducer. While it can be used for dynamic measurement, only qualitative results are generally obtainable. Force accuracy ranges from approximately ± 5% to ± 25% depending on the consistency of the measurement and actuation system, the repeatability tolerance held in manufacturing, and the use of part calibration.

Accuracy should not be confused with resolution. The force resolution of FSR devices is better than

± 0.5% of full use force.

2. Choose the Sensor that Best Fits the Geometry of Your Application

Usually sensor size and shape are the limiting parameters in FSR integration, so any evaluation part should be chosen to fit the desired mechanical actuation system. In general, standard FSR products have a common semiconductor make-up and only by varying actuation methods (e.g. overlays and actuator areas) or electrical interfaces can different response characteristics be achieved.

3. Set-up a Repeatable and Reproducible Mechanical Actuation System

When designing the actuation mechanics, follow these guidelines to achieve the best force repeatability:

- Provide a consistent force distribution. FSR response is very sensitive to the distribution of the applied force. In general, this precludes the use of dead weights for

characterization since exact duplication of the weight distribution is rarely repeatable cycle-to-cycle. A consistent weight (force) distribution is more difficult to achieve than merely obtaining a consistent total applied weight (force). As long as the distribution is the same cycle-to-cycle, then repeatability will be maintained. The use of a thin elastomer between the applied force and the FSR can help absorb error from inconsistent force distributions.

- Keep the actuator area, shape, and compliance constant. Charges in these parameters significantly alter the response characteristic of a given sensor. Any test, mock-up, or evaluation conditions should be closely matched to the final use conditions. The greater the cycle-to-cycle consistency of these parameters, the greater the device repeatability. In human interface applications where a finger is the mode of actuation, perfect control of these parameters is not generally possible. However, human force sensing is somewhat inaccurate; it is rarely sensitive enough to detect differences of less than ± 50%.

- Control actuator placement. In cases where the actuator is to be smaller than the FSR active area, cycle-to-cycle consistency of actuator placement is necessary. (Caution: FSR layers are held together by an adhesive that surrounds the electrically active areas. If force is applied over an area which includes the adhesive, the resulting response characteristic will be drastically altered.) In an extreme case (e.g., a large, flat, hard actuator that bridges the bordering adhesive), the adhesive can present FSR actuation

- Keep actuation cycle time consistent. Because of the time dependence of the FSR resistance to an applied force, it is important when characterizing the sensor system to assure that increasing loads
(e.g. force ramps) are applied at consistent rates (cycle-to-cycle). Likewise, static force measurements must take into account FSR mechanical setting time. This time is dependent on the mechanics of actuation and the amount of force applied and is usually on the order of seconds.

4. Use the Optimal Electronic Interface

In most product designs, the critical characteristic is Force vs. Output Voltage, which is controlled by the choice of interface electronics. A variety of interface solutions are detailed in the TechNote section of this guide. Summarized here are some suggested circuits for common FSR applications.

- For FSR Pressure or Force Switches, use the simple interfaces detailed on pages 16 and 17.

- For dynamic FSR measurements or Variable Controls, a current-to-voltage converter (see pages 18 and 19) is recommended. This circuit produces an output voltage that is inversely proportional to FSR resistance. Since the FSR resistance is roughly inversely proportional to applied force, the end result is a direct proportionality between force and voltage; in other words, this circuit gives roughly linear increases in output voltage for increases in applied force. This linearization of the response optimizes the resolution and simplifies data interpretation.

5. Develop a Nominal Voltage Curve and Error Spread

When a repeatable and reproducible system has been established, data from a group of FSR parts can be collected. Test several FSR parts in the system. Record the output voltage at various pre-selected force points throughout the range of interest. Once a family of curves is obtained, a nominal force vs. output voltage curve and the total force accuracy of the system can be determined.

6. Use Part Calibration if Greater Accuracy is Required

For applications requiring the highest obtainable force accuracy, part calibration will be necessary. Two methods can be utilized: gain and offset trimming, and curve fitting.

- Gain and offset trimming can be used as a simple method of calibration. The reference voltage and feedback resistor of the current-to-voltage converter are adjusted for each FSR to pull their responses closer to the nominal curve.

- Curve fitting is the most complete calibration method. A parametric curve fit is done for the nominal curve of a set of FSR devices, and the resultant equation is stored for future use. Fit parameters are then established for each individual FSR (or sending element in an array) in the set. These parameters, along with the measured sensor resistance (or voltage), are inserted into the equation to obtain the force reading. If needed, temperature compensation can also be included in the equation.

7. Refine the System

Spurious results can normally be traced to sensor error or system error. If you have any questions, contact Interlink Electronics' Sales Engineers to discuss your system and final data.

FSR Usage Tips *The Do's and Don'ts*

- **Do** follow the seven steps of the FSR Integration Guide.

- **Do**, if possible, use a firm, flat and smooth mounting surface.

- **Do** be careful if applying FSR devices to curved surfaces. Pre-loading of the device can occur as the two opposed layers are forced into contact by the bending tension. The device will still function, but the dynamic range may be reduced and resistance drift could occur. The degree of curvature over which an FSR can be bent is a function of the size of the active area. The smaller the active area, the less effect a given curvature will have on the FSR's response.

- **Do** avoid air bubbles and contamination when laminating the FSR to any surface. Use only thin, uniform adhesives, such as Scotch   brand double-sided laminating adhesives. Cover the entire surface of the sensor.

- **Do** be careful of kinks or dents in active areas. They can cause false triggering of the sensors.

- **Do** protect the device from sharp objects. Use an overlay, such as a polycarbonate film or an elastomer, to prevent gouging of the FSR device.

- **Do** use soft rubber or a spring as part of the actuator in designs requiring some travel.

- **Do not** kink or crease the tail of the FSR device if you are bending it; this can cause breaks in the printed silver traces. The smallest suggested bend radius for the tails of evaluation parts is about 0.1" [2.5 mm]. In custom sensor designs, tails have been made that bend over radii of 0.03" (0.8 mm). Also, be careful if bending the tail near the active area. This can cause stress on the active area and may result in pre-loading and false readings.

- **Do not** block the vent. FSR devices typically have an air vent that runs from the open active area down the length of the tail and out to the atmosphere. This vent assures pressure equilibrium with the environment, as well as allowing even loading and unloading of the device. Blocking this vent could cause FSRs to respond to any actuation in a non-repeatable manner. Also note, that if the device is to be used in a pressure chamber, the vented end will need to be kept vented to the outside of the chamber. This allows for the measurement of the differential pressure.

- **Do not** solder directly to the exposed silver traces. With flexible substrates, the solder joint will not hold and the substrate can easily melt and distort during the soldering. Use Interlink Electronics' standard connection techniques, such as solderable tabs, housed female contacts, Z-axis conductive tapes, or ZIF (zero insertion force) style connectors.

- **Do not** use cyanoacrylate adhesives (e.g. Krazy Glue) and solder flux removing agents. These degrade the substrate and can lead to cracking.

- **Do not** apply excessive shear force. This can cause delamination of the layers.

- **Do not** exceed 1mA of current per square centimeter of applied force (actuator area). This can irreversibly damage the device.

Evaluation Parts

Descriptions and Dimensions

Part No. 400 (0.2" Circle)

0.300 [7.6]

1.500
[38.1]

0.250 [6.4]

Figure
5:

0.720
[18.3]

2.130
[54.1]

0.300 [7.6]

Figure 6:
Part No. 402 (0.5" Circle)
0.002" [0.05] Acrylic
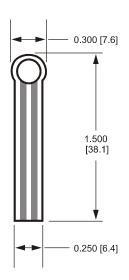
Active Area: 0.2" [5.0] diameter

Connector options

a.   No connector
b.   Solder Tabs (not shown)
c.   AMP Female connector
     Active Area: 0.5" [12.7] diameter

Nominal Thickness: 0.012" [0.30 mm]

Nominal thickness: 0.018" [0.46 mm]

Material Build:

Semiconductive   layer 0.004" [0.10] PES **Spacer adhesive**

0.002" [0.05] Acrylic

Conductive layer 0.004" [0.10] PES

Rear adhesive

Material Build:

Semiconductive Layer 0.005" [0.13] Ultem

Spacer Adhesive

0.006" [0.15] Acrylic

Conductive Layer 0.005" [0.13] Ultem

Rear Adhesive

0.002" [0.05] Acrylic

Connector

a. No connector
b. Solder Tabs (not shown)
c. AMP Female connector

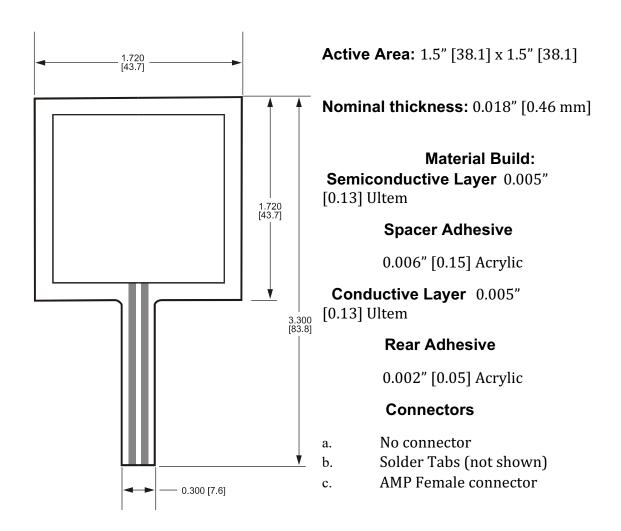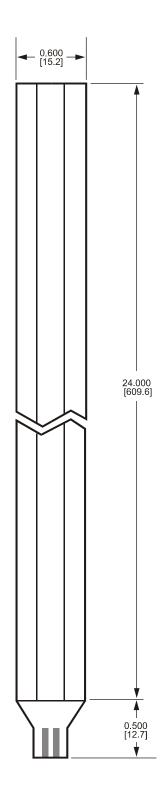*Dimensions in brackets: millimeters • Dimensional Tolerance: ± 0.015" [0.4] • Thickness Tolerance: ± 10%*

Active Area: 1.5" [38.1] x 1.5" [38.1]

Nominal thickness: 0.018" [0.46 mm]

Material Build:
Semiconductive Layer 0.005" [0.13] Ultem

Spacer Adhesive

0.006" [0.15] Acrylic

Conductive Layer 0.005" [0.13] Ultem

Rear Adhesive

0.002" [0.05] Acrylic

Connectors

a.   No connector
b.   Solder Tabs (not shown)
c.   AMP Female connector

Figure 7:

Part No. 406 (1.5" Square)

```
0.600
[15.2]
```

Active Area: 24" [609.6] x 0.25" [6.3]

Nominal thickness 0.135" [0.34 mm]

Material Build:
    Semiconductive Layer
    0.004" [0.10] PES
    Spacer Adhesive
    0.0035" [0.089] Acrylic
    Conductive Layer
    0.004" [0.10] PES
    Rear Adhesive
    0.002" [0.05] Acrylic
    Connectors
      a. No connector
      b. Solder Tabs (not shown)
      c. AMP Female connector

```
24.000
[609.6]

0.500
[12.7]
```

Figure 8
Part No. 408 (24" Trimmable Strip)

Dimensions in brackets: millimeters
Dimensional Tolerance: ± 0.015" [0.4]
Thickness Tolerance: ± 10%

General FSR Characteristics

These are typical parameters. The FSR is a custom device and can be made for use outside these characteristics. Consult Sales Engineering with your specific requirements.

Simple FSR Devices and Arrays

	VALUE	NOTES
Size Range	Max = 20" x 24" (51 x 61 cm) Min = 0.2" x 0.2" (0.5 x 0.5 cm)	Any shape
Device thickness	0.008" to 0.050" (0.20 to 1.25 mm)	Dependent on materials
Force Sensitivity Range	< 100 g to > 10 kg	Dependent on mechanics
Pressure Sensitivity Range	< 1.5 psi to > 150 psi (< 0.1 kg/cm^2 to > 10 kg/cm^2)	Dependent on mechanics
Part-to-Part Force Repeatability	± 15% to ± 25% of established nominal resistance	With a repeatable actuation system
Single Part Force Repeatability	± 2% to ± 5% of established nominal resistance	With a repeatable actuation system
Force Resolution	Better than 0.5% full scale	
Break Force (Turn-on Force)	20 g to 100 g (0.7 oz to 3.5 oz)	Dependent on mechanics and FSR build
Stand-Off Resistance	> 1MΩ	Unloaded, unbent
Switch Characteristic	Essentially zero travel	
Device Rise Time	1-2 msec (mechanical)	
Lifetime	> 10 million actuations	
Temperature Range	-30ºC to +70°C	Dependent on materials

	VALUE	NOTES

Maximum Current — I mA/cm^2 of applied force

Sensitivity to Noise/Vibration — Not significantly affected

EMI / ESD — Passive device

Lead Attachment — Standard flex circuit techniques

For Linear pots

	VALUE	**NOTES**
Positional Resolution	0.003" to 0.02" (0.075 to 0.5 mm)	Dependent on actuator size
Positional Accuracy	Better than ± 1% of full length	

FSR terminology is defined on pages 14 and 15 of this guide.

The product information contained in this document is designed to provide general information and guidelines only and must not be used as an implied contract with Interlink Electronics. Acknowledging our policy of continual product development, we reserve the right to change without notice any detail in this publication. Since Interlink Electronics has no control over the conditions and method of use of our products, we suggest that any potential user confirm their suitability before adopting them for commercial use.

Glossary of Terms

Active Area The area of an FSR device that responds to normal force with a decrease in resistance.

Actuator The object which contacts the sensor surface and applies force to FSRs.

Applied Force The force applied by the actuator on the active area of the sensor.

Array Any grouping or matrix of FSR sensors which can be individually actuated and measured.

Break Force The minimum force required, with a specific actuator size, to cause the onset of the FSR response.

Cross-talk Measurement noise or inaccuracies of a sensor as a result of the actuation of another sensor on the same substrate. See also false triggering.

Driff The change in resistance with time under a constant (static) load. Also called resistance drift.

Durometer The measure of the hardness of rubber.

EMI Electromagnetic interference.

ESD Electrostatic discharge.

False triggering The unwanted actuation of a FSR device from unexpected stimuli; e.g., bending or cross-talk.

Fixed Resistor The printed resistor on linear potentiometers that is used to measure position.

Footprint Surface area and force distribution of the actuator in contact with the sensor surface.

Force Resolution The smallest measurable difference in force.

FSR™ Force Sensing Resistors®. A polymer thick film device with exhibits a decrease in resistance with an increase in force applied normal to the device surface.

Graphic Overlay A printed substrate that covers the FSR. Usually used for esthetics and protection.

Housed Female A stitched on AMP connector with a receptacle (female) ending. A black plastic housing protects the contacts. Suitable for removable ribbon cable connector and header pin attachment.

Hysteresis In a dynamic measurement, the difference between instantaneous force measurements at a given force for an increasing load versus a decreasing load.

Interdigitating Electrodes The conductor grid. An interweaving pattern of linearly offset conductor traces used to achieve electrical contact. This grid is shunted by the semiconductor layer to give the FSR response.

Lead Out or Busing System The method of electrically accessing each individual sensor.

Lexan® Polycarbonate. A substrate used for graphic overlays and labels. Available in a variety of surface textures.

Melinex® A brand of polyester(PET). A substrate with lower temperature resistance than Ulterm® or PES, but with excellent flexibility and low cost. Similar to Mylar™.

Part or Device The FSR. Consists of the FSR semiconductive material, conductor, adhesives, graphics or overlays, and connectors.

PES Polyethersulfone. A transparent substrate with excellent temperature resistance, moderate chemical resistance, and good flexibility.

Pin Out The descriptions of a FSR's electrical access at the connector pad (tail).

Repeatability The ability to repeat, within a tolerance, a previous response characteristic.

Response Characteristic The relationship of force or pressure vs. resistance.

Saturation Pressure The pressure level beyond with the FSR response characteristic deviates from its inverse power law characteristic. Past the saturation pressure, increases in force yield little or no decrease in resistance.

Sensor Each area of the FSR device that is independently force sensitive (as in an array).

Solder-tabs Stitched on AMP connectors with tab endings. Suitable for direct PC board connection or for soldering to wires.

Space and Trace The widths of the gaps and fingers of the conductive grid; also called pitch.

Spacer Adhesive The adhesive used to laminate FSR devices tighter. Dictates stand-off.

Stand-off The gap or distance between the opposed polymer film layers when the sensor in unloaded and unbent.

Stand-off Resistance The FSR resistance when the device is unloaded and unbent.

Substrate Any base material on which the FSR semi-conductive or metallic polymers are printed. (For example, polyetherimide, polyethersulforne and polyester films).

Tail The region where the lead out or busing system terminates. Generally, the tail ends in a connector.
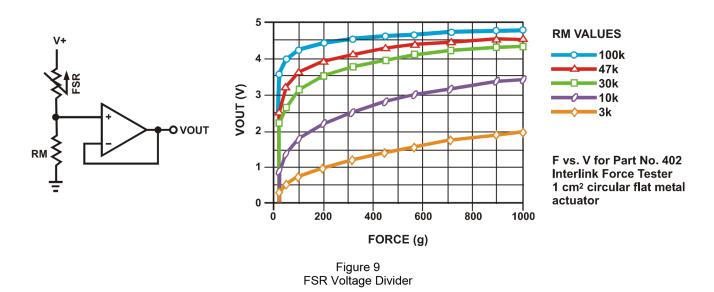
Ulterm®   Polyetherimide (PEI). A yellow, semi-transparent substrate with excellent temperature and chemical resistance and limited flexibility.

Interlink Electronics, Inc. holds international patents for its Force Sensign Resistor technology.
FSR is a trademark and Force Sensing Resistors is a registered trademark of Interlink Electronics. Interlink and the six dot logotype are registered marks or Interlink Electronics.

Ultem and Lexan are registered trademarks of G.E., Melinex is a registered trademark of ICI, and Mylar is a trademark of E.I. Dupont & Co.

Suggested Electrical Interfaces

Basic FSRs

Figure 9
FSR Voltage Divider

FSR Voltage Divider

For a simple force-to-voltage conversion, the FSR device is tied to a measuring resistor in a voltage divider configuration. The output is described by the equation:
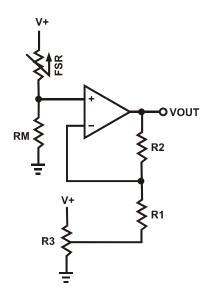
$$VOUT = (V+) / [1 + RFSR/RM].$$

In the shown configuration, the output voltage increases with increasing force. If RFSR and RM are swapped, the output swing will decrease with increasing force. These two output forms are mirror images about the line VOUT = (V+) / 2.

The measuring resistor, RM, is chosen to maximize the desired force sensitivity range and to limit current. The current through the FSR should be limited to less than 1 mA/square cm of applied force. Suggested opamps for single sided supply designs are LM358 and LM324. FET input devices such as LF355 and TL082 are also good. The low bias currents of these op-amps reduce the error due to the source impedance of the voltage divider.

A family of FORCE vs. VOUT curves is shown on the graph above for a standard FSR in a voltage divider configuration with various RM resistors. A (V+) of +5V was used for these examples.

Adjustable Buffers

Similar to the FSR Voltage Divider, these interfaces isolate the output from the high source impedance of the Force Sensing Resistor. However, these alternatives allow adjustment of the output offset and gain.

In Figure 10, the ratio of resistors R2 and R1 sets the gain of the output. Offsets resulting from the non-infinite FSR resistance at zero force (or bias currents) can be trimmed out with the potentiometer, R3. For best results, R3 should be about one-twentieth of R1 or R2. Adding an additional pot at R2 makes the gain easily adjustable. Broad range gain adjustment can be made by replacing R2 and R1 with a single pot.

Figure 10

The circuit in Figure 11 yields similar results to the

Adjustable Buffer

previous one, but the offset trim is isolated from the adjustable gain. With this separation, there is no constraint on values for the pot. Typical cal for R5 and the pot are around 10kΩ.
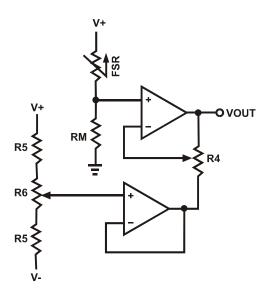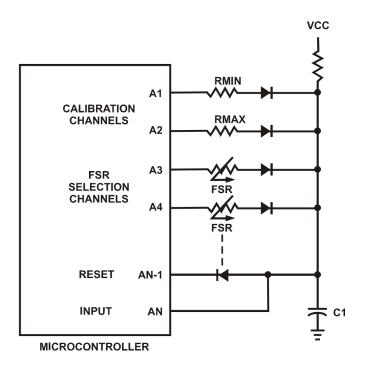

Figure 11

Adjustable Buffer

Figure 12
Multi-Channel FSR-to-Digital Interface

Multi-Channel to FSR-to-Digital Interface

Sampling Cycle (any FSR channel):

The microcontroller switches to a specific FSR channel, toggling it high, while all other FSR channels are toggled low. The RESET channel is toggled high, a counter starts and the capacitor C1 charges, with its charging rate controlled by the resistance of the FSR (t ~ RC). When the capacitor reaches the high digital threshold of the INPUT channel, the counter shuts off, the RESET is toggled low, and the capacitor discharges.

The number of "counts" it takes from the toggling of the RESET high to the toggling of the INPUT high is proportional to the resistance of the FSR. The resistors RMIN and RMAX are used to set a minimum and maximum "counts" and therefore the range of the "counts". They are also used periodically to re-calibrate the reference. A sampling cycle for RMIN is run, the number of "counts" is stored and used as a new zero. Similarly, a sampling cycle for RMAX is run and the value is stored as the maximum range (after subtracting the RMIN value). Successive FSR samplings are normalized to the new zero. The full range is "zoned" by dividing the normalized maximum "counts" by the number of desired zones. This will delineate the window size or width of each zone.

Continual sampling is done to record changes in FSR resistance due to change sin force. Each FSR is selected sequentially.
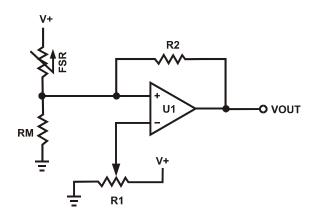

Figure 13
FSR Variable Force Threshold Switch

FSR Variable Force Threshold Switch

This simple circuit is ideal for applications that require on-off switching at a specified force, such as touchsensitive membrane, cut-off, and limit switches. For a variation of this circuit that is designed to control relay switching, see the following page.

The FSR device is arranged in a voltage divider with RM. An op-amp, U1, is used as a comparator. The output of U1 is either high or low. The non-inverting input of the op-amp is driven by the output of the divider, which is a voltage that increases with force. At zero force, the output of the op-amp will be low. When the voltage at the non-inverting input of the op-amp exceeds the voltage of the inverting input, the output of the op-amp will toggle high. The triggering voltage, and therefore the force threshold, is set at the inverting input by the pot R1. The hysteresis, R2, acts as a "debouncer", eliminating any multiple triggerings of the output that might occur.

Suggested op-amps are LM358 and LM324. Comparators like LM393 also work quite well. The parallel combination of R2 with RM is chosen to limit current and to maximize the desired force sensitivity range. A typical value for this combination is about 47kΩ.

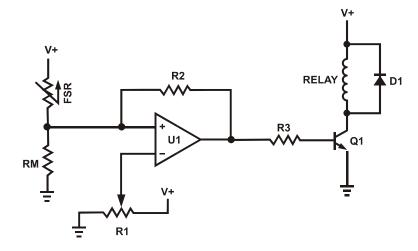The threshold adjustment pot, R1, can be replaced by two fixed value resistors in a voltage divider configuration.

Figure 14
FSR Variable Force Threshold Relay Switch

FSR Variable Force Threshold Relay Switch

This circuit is a derivative of the simple FSR Variable Force Threshold Switch on the previous page. It has use where the element to be switched requires higher current, like automotive and industrial control relays.

The FSR device is arranged in a voltage divider with RM. An op-amp, U1, is used as a comparator. The output of U1 is either high or low. The non-inverting input of the op-amp sees the output of the divider, which is a voltage that increases with force. At zero force, the output of the op-amp will be low. When the voltage at the non-inverting input of the op-amp exceeds the voltage of the inverting input, the output of the op-amp will toggle high. The triggering voltage, and therefore the force threshold, is set at the inverting input by the pot R1. The transistor Q1 is chosen to match the required current specification for the relay.

Any medium power NPN transistor should suffice. For example, an NTE272 can sink 2 amps, and an NTE291 can sink 4 amps. The resistor R3 limits the base current (a suggested value is 4.7kΩ). The hysteresis resistor, R2, acts as a "debouncer', eliminating any multiple triggerings of the output that might occur.

Suggested op-amps are LM358 and LM324. Comparators like LM393 and LM339 also work quite well, but must be used in conjunction with a pull-up resistor. The parallel combination of R2 with RM is chosen to limit current and to maximize the desired force sensitivity range. A typical value for this combination is about 47kΩ.

The threshold adjustment pot, R1, can be replaced by two fixed value resistors in a voltage divider configuration. The diode D1 is included to prevent flyback, which could harm the relay and the circuitry.

FSR Current-to-Voltage

Converter

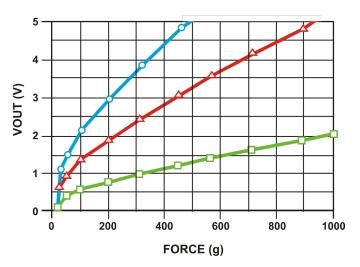In this circuit, the FSR device is the input of a current-to-voltage converter. The output of this amplifier is described by the equation:

$$VOUT = VREF \cdot [-RG/RFSR].$$

With a positive reference voltage, the output of the op-amp must be able to swing below ground, from 0V to –VREF, therefore dual sided supplies are necessary. A negative reference voltage will yield a positive output swing, from 0V to +VREF.

$$VOUT = (-RG \cdot VREF) /RFSR.$$

VOUT is inversely proportional to RFSR. Changing RG and/or VREF changes the response slope. The following is an example of the sequence used for choosing the component values and output swing:

RG VALUES
- 7.5k
- 4.7k
- 1.5k

F vs. V for Part No. 402 Interlink Force Tester 1 cm² circular flat metal actuator

For a human-to-machine variable control device, like a joystick, the maximum force applied to the FSR is about 1kg. Testing of

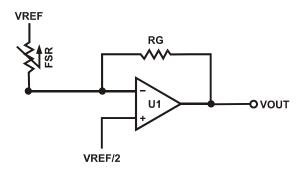a typical FSR shows that the corresponding RFSR at 1kg is about 4.6kΩ. If VREF is –

5V, and an output swing of 0V to +5V is desired, then RG should be approximately

equal to this minimum RFSR. RG is set at 4.7kΩ. A full swing of 0V to +5V is thus achieved. A set of FORCE vs. VOUT curves is shown in Figure 15 for a standard FSR using this interface with a variety of RG values.

The current through the FSR device should be limited to less than 1 mA/square cm of applied force. As with the voltage divider circuit, adding a resistor in parallel with RFSR will give a definite rest voltage, which is essentially a zero-force intercept value. This can be useful when resolution at low forces is desired.

Figure 16
Add'l FSR Current-to-Voltage Converter

These circuits are a slightly modified version of the current-to-voltage converter detailed on the previous page. Please refer to it for more detail.

The output of Figure 16 is described by the equation:

$$VOUT = [VREF/2] * [1-RG/RFSR]$$

The output swing of this circuit is from (VREF/2) to 0V. In the case where RG is greater than RFSR, the output will go into negative saturation.

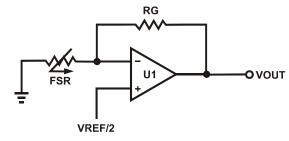Figure 17
Add'l FSR Current-to-Voltage Converter

The output of Figure 17 is described by the equation:

$$VOUT = VREF/2 \cdot [1 + RG/RFSR].$$

The output swing of this circuit is from (VREF/2) to VREF. In the case where RG is greater than RFSR, the output will go into positive saturation.

Additional FSR Current-to-Voltage Converters

For either of these configurations, a zener diode placed in parallel with RG will limit the voltage built up across RG. These designs yield one-half the output swing of the previous circuit, but only require single sided supplies and positive reference voltages. Like the preceding circuit, the

current through the FSR should be limited to less than 1 mA/square cm of applied force.
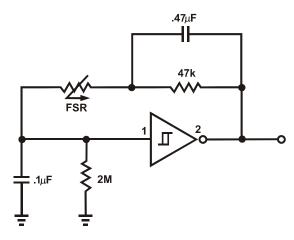
Suggested op-amps are LM358 and LM324.

Figure 18
FSR Schmitt Trigger Oscillator

FSR Schmitt Trigger Oscillator

In this circuit, an oscillator is made using the FSR device as the feedback element around a Schmitt Trigger.

In this manner, a simple force-to-frequency converter is made. At zero force, the FSR is an open circuit. Depending on the last stage of the trigger, the output remains constant, either high or low. When the FSR is pressed, the oscillator starts, its frequency increasing with increasing force. The 2MΩ resistor at the input of the trigger insures that the oscillator is off when FSRs with non-infinite resistance at zero force are used. The 47kΩ resistor and the 0.47 μF capacitor control the force-to-frequency characteristic. Changes in the

"feel" of this circuit can be made by adjusting these values. The 0.1μF capacitor controls the frequency range of the oscillator. By implementing this circuit with CMOS or TTL, a digital process can be controlled by counting leading and/or trailing edges of the oscillator output. Suggested Schmitt Triggers are CD40106, CD4584 or 74C14.

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