DEVELOPMENT OF A TELEREHABILITATION SOLUTION FOR REMOTE MONITORING AND CARE

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A THESIS SUBMITTED

FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

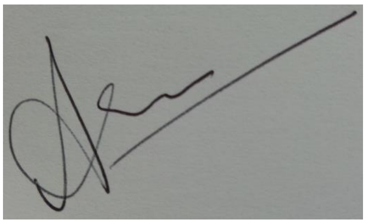
NATIONAL UNIVERSITY OF SINGAPORE

2016

DECLARATION

I hereby declare that this thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis.

This thesis has also not been submitted for any degree in any university previously.



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4 January 2016

Acknowledgements

First and foremost, I owe sincere gratitude to my supervisor, Prof. Tan Kok Kiong. He has been instrumental in guiding me in the right path whenever I seemed to deviate or lose focus in the research direction. This thesis could not be finished without his patient and careful guidance, constant support, and encouragement.

I would like to thank Prof. Arthur Tay and Prof. Justin Pang for their kind encouragement and constructive suggestions, which have improved the quality of my work. I shall extend my thanks to all my colleagues at the Mechatronics & Automation Lab, for their companionship during my stay at the National University of Singapore. I truly appreciate the support from my collaborators Helen Hoenig from Duke University as well as Prof. Gerald Koh from NUH.

I would also like to thank my colleagues at National Instruments Singapore Pte Ltd, especially Chandran Nair, for the support and understanding throughout the years. I would not be able to do this without their continued backing and I am grateful for that. My sincere thanks to EDB Singapore as well for providing me with the financial support over the course of my study.

Finally, special thanks to my friends and family for the abundance of love, support and encouragement over the years. Nothing would have been possible without them.

Contents

Summary

Access to proper medical care is limited to the mass living in rural settings due to the uneven distribution of medical resources and difficulties in travelling to the distant hospitals. These challenges can be addressed by simply making use of the existing communication infrastructure. This approach to medical care (Telemedicine) has been getting increasing attention over the past few decades. In Telemedicine, medical consultation over a distance is realised by making use of telecommunication technologies, such as the Internet. It is currently being used for many speciality clinical care applications like dermatology, cardiology, oncology, etc., and studies have shown that the user acceptance of such services has strong correlation with the stability of the communication link. However, sustaining a satisfactory audiovisual communication link is challenging, especially in developing countries, due to the limited infrastructure developments. Even in developed countries like Singapore, with rapidly ageing population dilemma, high speed Internet connection comes at a premium which is ill-afforded by the needy. As such, the need for a Telemedicine system that can function satisfactorily under low-speed and greatly fluctuating bandwidth conditions is high.

One area of Telemedicine that is increasingly being researched in the past decade is Telerehabilitation, which aims to deliver physical rehabilitation services. Generally, Telerehabilitation systems require the spatial information of the patient for proper diagnosis and currently it is achieved by using 3D-video cameras and wearable sensors. However, 3D-video incurs huge payload and the wearable sensors are prone to high inter-rater measurement errors. This thesis presents the design and development of a comprehensive Telerehabilitation system that has the necessary intelligence to function effectively under inconsistent bandwidth conditions. The proposed framework is formulated with audiovisual communication with a streaming algorithm that is able to detect the available bandwidth and adapt the video parameters accordingly so as to ensure the consultation session is uninterrupted. To provide important spatial information of the patient's movements during rehabilitation exercises, skeleton tracking algorithm of Microsoft Kinect sensor is proposed. This replaces the need for the high payload 3D-video and the error prone wearable sensor systems. In order to assist the physician in easy diagnosis, exercise performance of the patient is quantified and a report generation tool is integrated into the system for record keeping. The system also incorporates a readily available physiological sensor as an add-on that can monitor the patients' heart rate, temperature, etc. during exercises.

In order to validate its performance, the developed system was tested under low and fluctuating bandwidth environments and a survey was conducted to collect feedback from users, including medical professionals and therapists. The results proved smooth functioning of the Telerehabilitation system and it is shown to be maintaining an acceptable level of performance, based on the survey feedback. The system was also validated for its ability to perform standardised rehabilitation assessments in practice today and the results demonstrated strong positive correlation. Thus, the work presented in this thesis is important in addressing the healthcare delivery challenge and this thesis represents the first step in that direction.

List of Abbreviations

ICT .... Information and Communication Technologies

ITU .... International Telecommunications Union

IDA .... Infocomm Development Authority

VR .... Virtual Reality

TCP .... Transmission Control Protocol

NAT .... Network Address Translation

WPF .... Windows Presentation Foundation

SDK .... Software Development Kit

FPS .... Frames Per Second

BW .... Bandwidth

2D .... Two Dimensional

3D .... Three Dimensional

HSL .... Hue Saturation Luminance

FIFO .... First In First Out

TR .... Telerehabilitation

PT/OT .... Physical Therapist / Occupational Therapist

AIMD .... Additive Increase Multiplicative Decrease

CQ .... Compression Quality

F.M. .... Fine Motor

G.M. .... Gross Motor

D3 .... Dynamic Data Display

CoM .... Centre of Mass

MoI .... Moment of Inertia

TUG .... Timed Up and Go

SST .... Sit to Stand Test

FRT .... Functional Reach Test

POMA-G ..... Performance Oriented Mobility Assessment for Gait

DLL .... Dynamic Link Library

SEM .... Sensor Electronic Module

SPP .... Serial Port Profile

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Chapter 1

Introduction

The healthcare sector is facing numerous challenges due to rising costs, ageing populations, and increasing number of emerging disease threats around the world. Innovative use of technology can potentially address some of these challenges and help to deliver proper medical care to the mass while reducing cost and making optimal use of limited resources in terms of medical professionals and facilities. Several healthcare organisations are focusing on new methods of delivering quality healthcare in a timely, cost effective, and efficient manner using advanced technology solutions [9].

With the proliferation of the Internet and related technologies, it has become easier to design and realise such systems. As such, Information and Communication Technologies (ICT) sector has much to offer in this regard in both developed and less economically developed countries. Sending of data over the Internet is now common in almost all parts of the world and the above mentioned challenges can be addressed with the proper design of a system, at least to some extent. Delivery of such medical services over the distance using telecommunications technology is termed Telemedicine. According to the World Health Organisation (WHO), Telemedicine is defined as follows:

The delivery of health care services, where distance is a critical factor, by all health care professionals using information and communication technologies for the exchange of valid information for diagnosis, treatment and prevention of disease and injuries, research and evaluation, and for the continuing education of health care providers, all in the interests of advancing the health of individuals and their communities [10].

Telemedicine allows for evaluation, diagnosis, monitoring, consultation, and follow-up of patients without the need to travel while overcoming geographical barriers and increasing access to cost-effective and high quality healthcare services [11]. Even in countries like Singapore, where geographical barriers are minimal for accessing medical care, Telemedicine can be of great use especially considering its growing population age and the difficulties the elderly face while travelling to the doctor. Due to the difficulty for the elderly in travelling to hospital, home care nurses are becoming highly in demand. According to a recent news article in Singapore, the average waiting time for a patient to receive home nursing care can take up to seven days due to the limited supply of staff [12] and Telemedicine is potentially an alternative solution in such cases.

Although Singapore is a developed country with good ICT infrastructure, the network speed can be highly inconsistent and high speed Internet is still not accessible to many in the society. This thesis presents the design and development of a Telemedicine application with focus on physical rehabilitation delivery, so termed Telerehabilitation, in fluctuating network conditions. The developed system is designed while incorporating the necessary medical knowledge so that it is not a purely engineering solution, but rather a comprehensive one, which in fact is useful one to the patients and medical professionals alike in delivering reliable Telerehabilitation services in low-bandwidth conditions.

1.1 Ageing Demography of Singapore

Population aging is a phenomenon common in countries across the world. According to the United Nations World Population Ageing Report 2013, older persons are projected to exceed the number of children for the first time in 2047. Currently around 65% of the world's older persons live in developing countries and the number is expected to increase to 80% by 2050 [13]. This issue is expected to bring major social and economic consequences in terms of having a proper support system, including that of the health sector, in place for the older population.

On a similar note, as the country is experiencing the slowest population growth, ageing population has become the number one challenge for Singapore to address going forward after celebrating the 50th birthday in 2015. According to the Singapore Department of Statistics, in 2015, the median age of the resident population in Singapore is 39.6 years and 11.8% of the total population are made up of residents aged 65 and above. Figure 1.1 shows the age pyramid of resident population of 2005 and 2015 for male and female residents and one can easily imagine the chart's shape in next 10 years' time if the birth rate continues at the current pace [1].

Another alarming factor, and almost always connected to the issues of low

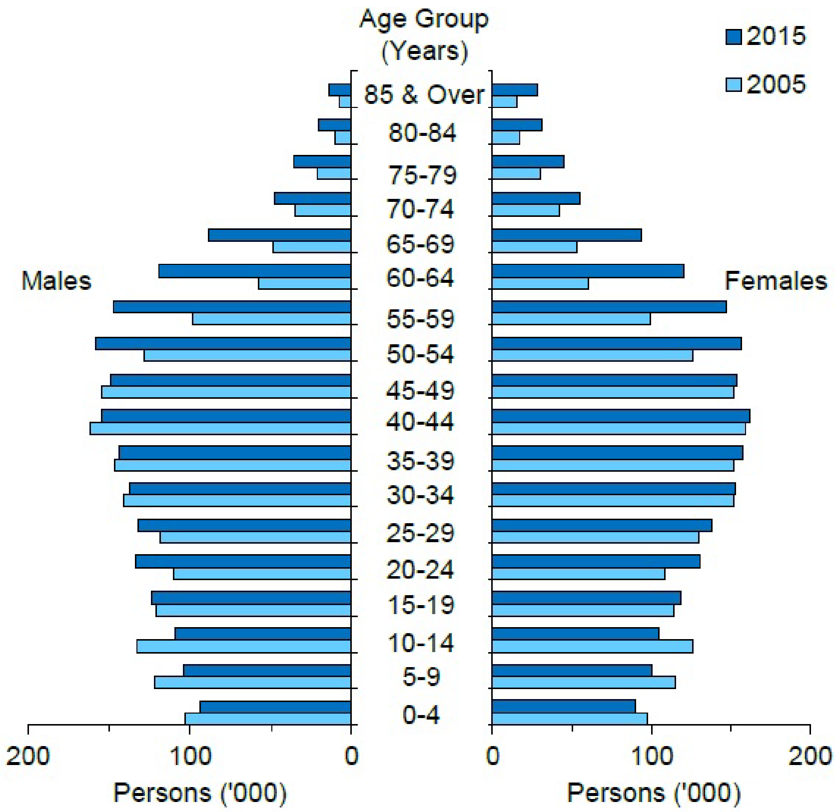


Figure 1.1: Age pyramid of resident population in Singapore [1]

birth rate, is the ratio of working adults to elderly (above age 65). Currently this ratio stands at around 5.7 and by 2030, it is expected that there would be only 2 working adults to support an elderly in Singapore as shown in Fig. 1.2 [1]. Moreover, according to this report [14], elderly population living alone in Singapore may rise to 83,000 by 2030. This means that ensuring these elderly have easy access to proper medical care is going to be a challenge. One way to address this challenge is by making use of technology, potentially by means of Telemedicine solutions which, if broadly deployed, can become normalcy in terms of going for regular checkups or follow-up visits to the doctor while not having to go through the hassle of physically going there. As Singapore moves towards becoming the world's first Smart Nation [15], use of technology is becoming more

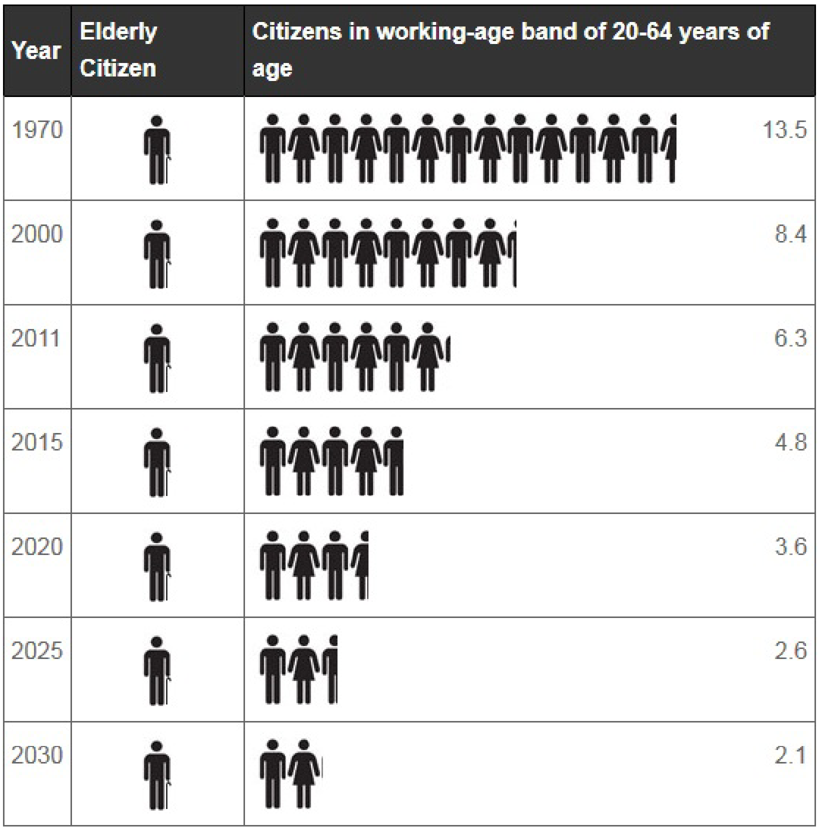


Figure 1.2: Singapore's declining old-age support ratio [1]

and more common as the country is trying to improve the lives of its citizens while building stronger communities. Smart homes with connected devices are going to be realised in the near future and Telemedicine can definitely be complementary to such a system.

1.2 Internet Penetration Around the World and Singapore

Although basic Internet infrastructure is present in most parts of the world today, often the connection is suitable only for low-speed applications. Higher speed connections come at a premium, which is ill-afforded by the needy. According to the 2015 International Telecommunications Union (ITU) report [16], there are 3.2 billion Internet users around the world of which around 68% come from developing countries. However, the average network speed available to the people around the world is limited; even more so in the case of developing countries [17].

The 2014 statistical report regarding the number of broadband Internet users from the Infocomm Development Authority (IDA) of Singapore is shown in Fig.1.3 [2]. From the figure, it is clear that there are around 300,000 residential users with a maximum downstream Internet speed of 2Mbps or below. It does not reduce as time progresses and based on the chart history, it is expected to be there in the future as well. If one considers the speed of 10Mbps or below, the number will rise to 500,000 households. This is a significant proportion of the country's population. Although the maximum speed mentioned here is considered high enough for a good quality video conversation to take place, in reality the user will be able to enjoy a fraction of that on average, especially for uploading data. Fig.1.4 reveals the average upload throughput in different Internet speeds using different broadband plans offered by telecommunications companies in Singapore [3]. It is clear that, for maximum speeds of 50Mbps or below, the uploading speed is almost non-existent. Rather, it is very low, in terms of kbps, and that is the reason it is not evident in the figure.

Of course, the user can always purchase a high speed Internet access at home with a high premium, especially with the latest introduction of fibre optic cable network. But that is exactly where the challenge lies in the case of the less fortunate in the society wherein most of them are not able to afford such a service. Figure 1.5 details the different Internet speeds and their monthly minimum sub-

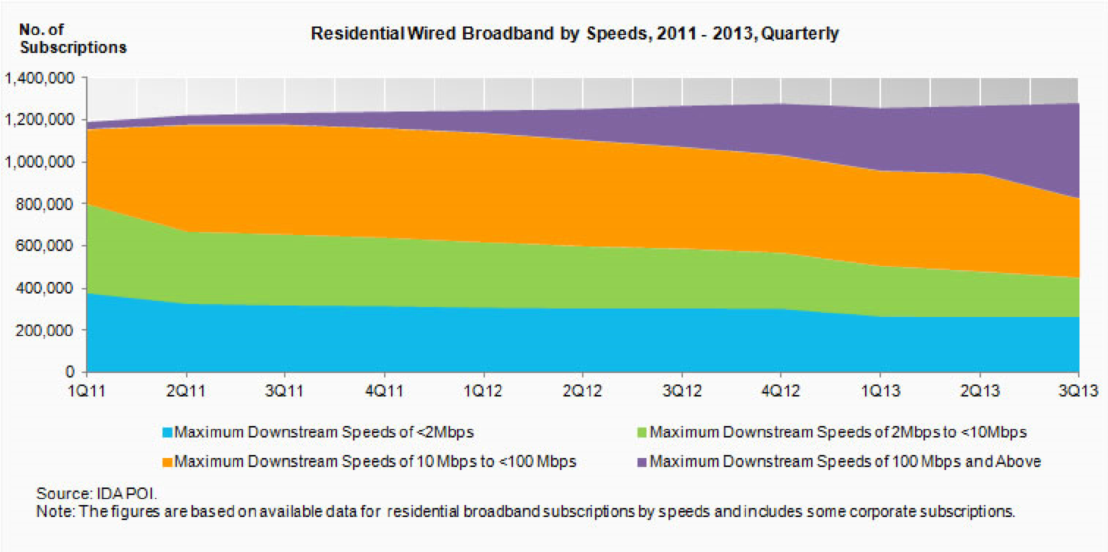


Figure 1.3: Residential broadband subscription in Singapore [2]

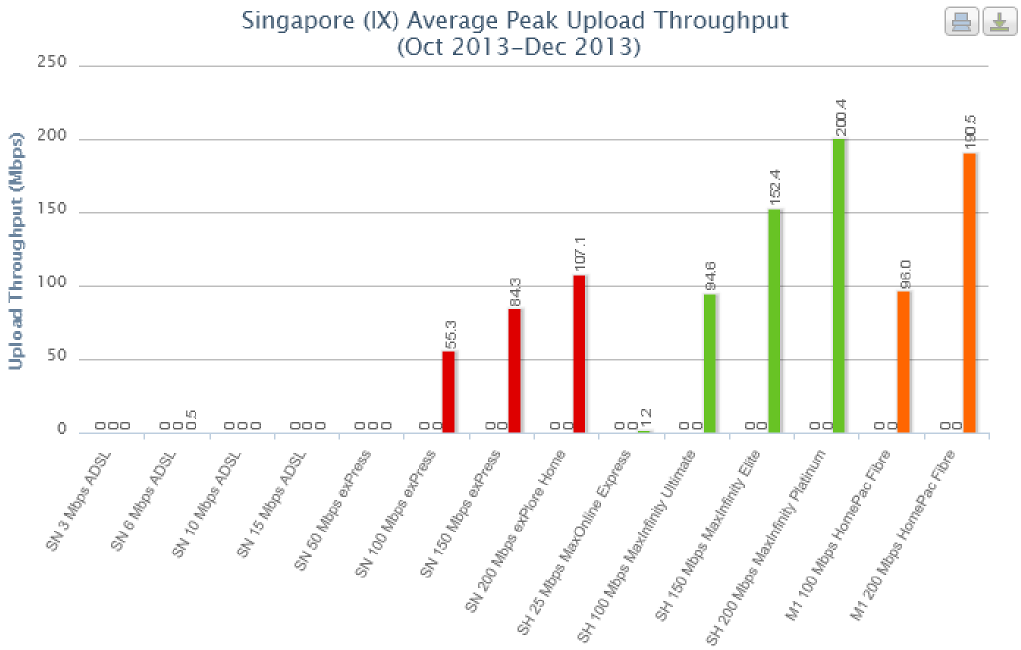


Figure 1.4: Average peak upload throughput for different broadband connections [3]

Figure 1.5: Minimum monthly broadband Internet subscription rates in Singapore [3]

scription rates offered by companies in Singapore [3]. A decent speed Internet costs upwards of $50 per month, according to Fig.1.5; even then, the service normally specifies the maximum speed it provides, and not a sustainable one, which fluctuates widely from time to time. This substantiates the need for an application that allows the Telemedicine sessions to progress smoothly even at a low available Internet speed.

1.3 Literature Review- Telemedicine Solutions

Telemedicine is often used synonymously to Telehealth and Telecare, which all essentially mean delivery of medical information using telecommunication technologies over a distance for diagnosis or educational purposes. In the early days, Telemedicine services were relying on telephony and telegraph services.

Later on, radio and space technologies were utilised and from the 1990s onwards, digital technologies were widely used to carry out Telemedicine services, which coincide with the advent of telecommunications technologies and the Internet. The key technological drivers for Telemedicine include computing and information technology, network and telecommunications infrastructure, and technology-led societies, whereas the key non-technological drivers include governmental health policies, cost reduction, extension of access to healthcare services etc.[18].

A Telemedicine system can be classified on the basis of the type of interaction between the patient and the doctor. Generally there are store-and-forward and real time Telemedicine systems. In store-and-forward system, the patient's medical data is acquired and stored locally and then forwarded to the doctor later on and it may take a longer time for the doctor to check the received data and get back to the patient through E-mail or telephone. In real time Telemedicine, the doctor and the patient are able to communicate simultaneously while the patient data is being acquired and sent over to the doctor. Videoconferencing is a regular way of real time Telemedicine systems nowadays. There is also a third type of Telemedicine, which is a hybrid between store-and-forward and real time systems [19].

A lot of research has been carried out in Telemedicine sector, in line with the advent of computer and telecommunication technology [20]. One of the initial versions of the current form of Telemedicine system was originated with NASA scientists developing a sophisticated biomedical telemetry and telecommunication system to monitor the physiological functions of astronauts in space [21]. The first complete Telemedicine system linking paraprofessionals and physician-patient encounter settings was installed in 1967, linking Boston's Logan Airport medical station and Massachusetts General Hospital, with remote diagnosis taking place through interactive television [22].

Telemedicine has been reported to be used in speciality clinical care applications such as anaesthesia [23], dermatology [24], cardiology [25], psychiatry [26], radiology [27], oncology [28] etc. from as early as the 1970s. Telemedicine has also been traditionally used in patient education [29] [30], home monitoring [31] [32], and continuing medical education [33] as well.

Compared to other forms of Telemedicine, Telerehabilitation has a comparatively short history, partly due to the nature of physical rehabilitation in which the human movements are subtle, complex, and occurs in three dimensional space. With the development of sophisticated optical and sensor based measurement, Telerehabilitation started to get increasing attention and it is evident from the research work conducted in this field in the past decade [34]. Generally, technology for Telerehabilitation can be classified as sensor based, image based, or virtual reality based.

There has been studies reported on using Telerehabilitation for caring for individuals with neurologic issues that was well received by the clinicians [35] [36], which are good examples of image-based Telerehabilitation. Some researchers in Australia successfully used sensor based system for Telerehabilitation that achieved high compliance rates [37]. Further work on this produced a real-time human movement classification system for home monitoring of patients [38]. A research team from Massachusetts Institute of Technology have developed a Telerehabilitation system that allows a therapist in a remote location to conduct treatment sessions, using a virtual-environment-based motor-training system, with a patient who is located at home [39]. The system gathered positives feedback from the users upon implementation and the results were promising for broader deployment [40].

There are reports on the acceptance level of Telemedicine solutions by the users, mainly the physicians/therapists and the patients. Early reviews and evaluations compared primarily synchronous real-time Telemedicine with traditional face-to-face consultation and found that the users of Telemedicine were for the most part satisfied [41] [42] [43]. In a more recent study conducted on patient satisfaction with Telemedicine, specifically focused on geriatrics patients, it was reported that a majority of the respondents (72%) felt the use of Telemedicine had a positive effect on their relationship with the health provider [44]. Comparing to another survey conducted earlier, the study reports that, the patients were more comfortable with the recent system due to fewer technical problems during the session. This emphasises the importance of having an uninterrupted communication during a Telemedicine session.

Similarly, patients' experiences of Telerehabilitation systems, such as the one reported in this home based care for patients after shoulder joint replacement [45], indicated that they felt safe, competent and strengthened in their daily exercise routines. Again, communication reliability and smoothness were noted to be the key factors behind the positive feedback from the users.

1.3.1 Low-bandwidth Telemedicine Solutions

Most video streaming applications are designed for broadband connections. Nevertheless, there are some works focusing on narrowband connections. Gualdi et al. developed a low-latency video streaming system that is able to transmit images in CIF format at 10 frames per second (fps) over GPRS with 1.73 seconds latency on average [46]. The system is specifically targeted at low-bandwidth networks, but the video quality is kept at the same low level even over the broadband networks. Lim et al. also developed a narrowband video stream solution, which achieved a modest frame rate over a GPRS connection [47].

Many works focused on adaptive streaming, whereby the bit-rate of the encoded images are adjusted based on the allowable bandwidth. Song and Golubchik devised an adaptive video streaming solution to deliver better video quality among other similar technologies [48]. However, Song gave emphasis to video quality rather than the efficiency of bandwidth usage that is important in the context of this work. There are also mainstream products such as Microsoft IIS Smooth Streaming [49], Adobe Flash Dynamic Streaming [50] and Apple HTTP Adaptive Bitrate Streaming [51]. However, all of these products are intended for use in broadcasts for mass entertainment purposes. Leijdekkers et al. proposed a tele-monitoring solution that allows caregivers to monitor patients in real-time [52]. The system proposed was more of a one-way monitoring system, where the caregivers are able to see the patients and there is no mention of the system's performance under low bandwidth connection.

A group of researchers used low-bandwidth network for sending over real-time ultrasound images of infant hip exam for a feasibility study [53]. This system, designed specifically for Teleultrasound transmission, although encountered significant loss of information, the panel evaluation failed to recognise any clinical difference between the original saved and the transmitted images and proved to be useful in low-bandwidth settings. In a separate study, another group of researchers from Australia developed a Telerehabilitation solution specially designed for total knee replacement to be used under low-bandwidth settings [54]. The system was set-up based on an ordinary telephone line connection, which was designed to send over audio-visual data at a fixed data rate. The system was well received by the therapists and patients alike and the participants were found to achieve treatment outcomes that were comparable to those achieved with traditional, face-to-face treatment.

To the best of the author's knowledge, there is no work reported that has specifically addressed the aforementioned issues and challenges of developing a tele-consultation platform for healthcare purposes under limited bandwidth settings. Each of the work attempts to address one (or a few) requirement(s), leaving the others intact or compromised.

1.3.2 Telemedicine Solutions in Singapore

Although a small city state, arguments for Telemedicine are compelling for Singapore. One argument is in its potential to export the medical expertise to other developing countries in the region. The other is to use Telemedicine solution for home Telecare as the country is facing an increasing ageing population issue. Those discharged patients can continue to receive consultation and monitoring through such solutions [55]. Some early work in Singapore reported using virtual reality (VR) for Telerehabilitation purposes [56]. Although a high cost solution with a VR glove and a tracking system that was tested in high speed network settings, it was proven to be beneficial in home-based healthcare delivery.

A recent study reported the use of biomechanical and kinematical in-game markers for assessment of patient disabilities. This VR based study facilitated quantitative feedback to the patient and can be potentially developed into a Telerehabilitation solution with further research, although the patient will need to wear the markers and connect up the hardware to use the system [57]. Another work was reported on using inertial measurement units integrated with Microsoft Kinect sensor in fusion for upper limb motion tracking. The report concludes that such low-cost applications using Kinect has high potential in home-based rehabilitation systems [58]. There was another recent study reported on the use of a Telerehabilitation system designed for stroke rehabilitation that uses a number of wearable devices as well as an iPad based software platform with Bluetooth communication. Although the system includes videoconferencing capabilities, it is not specifically designed for low-bandwidth environments [59]. The system is currently under trial and the results are expected to provide answers for the practicability of a Telerehabilitation intervention as well as its economic viability in Singapore settings.

Another research group focused on using Kinect for rehabilitation purposes, whereby the user is able to perform specific rehabilitation exercises from a list of selections and the saved data will be accessed by a therapist to be analysed [60] [61]. The web based system includes preset tests that would track the necessary joints accordingly and store the data on a cloud and it also enabled the therapist to remotely increase the motion range of exercises. There was, however, no further information on how a manual test would be performed, which may be different from the list of preset tests and the system was not developed for live consultation with the physician, but rather as a store-and-forward type of Telerehabilitation. Again, it was not a system designed particularly for low-bandwidth applications and thus transmitting the video data under such circumstances may still be a challenging task.

There are a number of studies reported on Telemedicine systems in this region and some of them use low-cost solutions to achieve the purpose. Although some studies are reported on using non-wearable sensor solutions for Telerehabilitation applications in the region, no prior work was found with a focus on enabling such a solution in highly fluctuating and unstable network settings.

1.4 Main Contributions

This thesis presents the development of a Telerehabilitation platform that is designed to function satisfactorily under limited bandwidth settings. The platform incorporates an algorithm to adapt the data rate, according to the available network conditions, by dynamically changing its video parameters. In addition, the solution makes use of Microsoft's Kinect sensor to employ it as an alternative for existing spatial data extraction tools, so that the depth data can be made available to the physicians even under constrained bandwidth environments.

In order to realise a remote physical rehabilitation delivery under low-bandwidth environments, the proposed system is designed with designated consultation categories, while incorporating the necessary medical know-how on the typical user requirements. The embedded rehabilitation tool in the developed system includes human body joint extraction methods to measure the linear and angular movements together with the capability to perform standard rehabilitation assessments. It also includes an automated data analysis algorithm to quantify the measured data.

An optional add-on to the system, a third party sensor package, is integrated into the developed platform to measure essential physiological data, such as heart rate, temperature, breath rate, etc. This enables the physician to have a better understanding of the patient's body response to the recommended exercises and this additional capability helps to make the Telerehabilitation system more comprehensive in terms of its usability. Experiments were conducted in many simulated network environments to test the system performance and then a survey was conducted among potential users, including therapists, to rate the quality of the delivered data. The results validated the systems capability to efficiently utilise the limited available bandwidth while ensuring a continuous consultation session.

1.5 Thesis Overview

This thesis is structured in three main parts. In the first part (Chapter 2), development of a basic framework for low-bandwidth communication is presented. In the second part (Chapter 3 - 5), improvements in the depth extraction as well as using it for Telerehabilitation purposes are presented. Finally, the third part (Chapter 6 & Chapter 7) presents the integration of these improvements together with integration of available third party hardware for physiological data measurement, to the existing framework, making it a comprehensive Telerehabilitation system.

With today's technological innovations, it is indeed possible to tap on to the existing infrastructure to make good use of it in the healthcare sector. Although today's medical consultations are mostly over face to face meetings, it has its own challenges with situations such as aging population, unevenly distributed medical resources, etc. Some of the simple follow up visits to the clinics or hospitals can potentially be done using the Internet facilities, by making use of the advent in communication technology. Studies have shown promising results using such technology in delivering medical care from a distance [62]. This is getting even more exciting considering the fact that the Internet penetration around the world is increasing as the years go by [16]. In light of these facts, the next chapter in this thesis (Chapter 2) presents the formulation of a basic audio-visual communication framework that can be used to connect the doctor and patient through a central server. Deviating from general-purpose objectives of off-the-shelf teleconferencing solutions, the system is customized to enable doctors and patients to be virtually linked over a broad range of connection speeds yet maintaining a satisfactory video/audio streaming experience to carry out remote diagnosis and assessment. This enables the users, even those from developing countries where the Internet speeds may be low due to the limited infrastructure developments, to benefit from the adaptive streaming solution. Specifically, a key objective is to maintain a frame rate of around 15 frames per second (fps) at various connection speeds through an appropriate selection and characterization of transmission protocols, encoding technologies and other innovations. Through the use of the Microsoft Kinect sensor, under low bandwidth conditions, the system allows a dynamic cropping of human body structure disregarding all other background information. The system also allows selective cropping for the user to discard the background, but send only the useful information. Finally, through the use of the adaptive streaming approach, the system is able to adapt the image quality to the network speed while maintaining the frame rate. Collectively, with these customized innovations incorporated, the system is able to perform video calls at a frame rate of around 15 fps even in the 128 kbps network. However, sending spatial information that is crucial for understanding the patients movement is still challenging under constrained network conditions.

Although face-to-face consultations are useful for basic visual examination of wounds and abrasions [63], certain Telerehabilitation assessments need the use of spatial information in order to accurately assess the patient's condition. Nevertheless, sending three-dimensional video data over low-bandwidth networks is extremely challenging, as mentioned by Hoenig et al. [64]. The authors of [64] realised that gait assessment performed using a 2D video from the frontal view was not sufficient to reliably assess foot placement while walking, as certain key information were not available to the physician to make an accurate diagnosis. Some other researchers had to use multiple cameras to get an acceptable video before making a confident decision and this of course came with huge data payload to be sent across the network, which is indeed a challenge in bandwidth scarce environments [65]. Other alternatives such as 2D-plus-Depth technology needed the use of specialised software at a high cost while the accuracy of the reconstructed 3D images has been often questionable [66]. In Chapter 3, the author presents an innovative way of extracting the key spatial information from the patient's movement during Telerehabilitation assessment with Kinect and then presenting the extracted data by using graph plots alongside the video to help physicians with assessments while imposing a minimum burden on the existing video data transfer. In the evaluation section, experiments were conducted for some common rehabilitation scenarios based on skeletal tracking and colour detection algorithms using the Microsoft Kinect sensor. The chapter concludes with detailed analysis of the extracted spatial data and discussion on its potential usability. Nevertheless, different rehabilitation sessions have different requirements. For example, assessment of fine motor movements need a higher frame rate video as compared to gross motor movements that require higher resolution video.

While many studies show the acceptability of Telerehabilitation [67] [68] [69], flexible solutions that are usable under low bandwidth network environments are rare. The aforementioned studies used systems with audio visual data exchange, which demand high bandwidth usage, and are designed for broadband connections [70] [71]. No existing Telerehabilitation solution was found that is designed to function satisfactorily under congested network conditions while adjusting the necessary parameters according to the physician's requirements. Chapter 4 introduces the development of a Telerehabilitation system with tailor-made consultation categories for users to choose from, depending on requirements. Each category, with its pre-set parameter values, is discussed in detail by demonstrating relevant rehabilitation exercises. A much improved bandwidth adaptation algorithm is also presented in this chapter for optimal utilisation of the inconsistent network conditions. The proposed algorithm is verified for its ability in adapting the content quality and for effectively utilising the network under constrained conditions. Experimental results presented in the chapter show that the system is able to perform effectively in each consultation category while the patient performs rehabilitation exercises. The chapter also presents a survey conducted on the video quality of the system under low bandwidth conditions and the results are encouraging, pointing to a potentially satisfactory performance of the application in bandwidth limited settings. While the platform was successfully tested for different assessment scenarios, it does not yet assist the physician with an automated analysis tool to quantify the patients performance across multiple sessions.

Earlier methods used in rehabilitation measurements were simple and inexpensive, but unreliable due to the inter-rater errors arising from manual measurements [72]. More modern tools are reliable, but require much more expertise to operate and cost is a limiting factor for their widespread use. As technology progressed, more sophisticated instruments and sensors were used for these measurements [73] [74]. However, the disadvantage is in terms of complexity of operation, cost, as well as the reliability since the sensor placement on the body plays an important role in the accuracy of the measurements and there are still chances for inter-rater errors. Moreover, studies have pointed out that most of these techniques need more than one person to operate and the entire process is more time consuming when compared to other medical consultations [75]. In contrast, Kinect is indeed a low-cost, portable alternative to this challenge as presented in this thesis. In this regard, Chapter 5 presents an improved framework for rehabilitation assessments, which can also be configured efficiently to perform standard rehabilitation tests in today's practice. The framework includes an automated data analysis as well as a report generation tool to analyse and present the assessment data. This was accomplished by designing a single-user platform that measures generic parameters, such as linear and angular data of selected body joints. Using the improved framework, some standard rehabilitation tests were chosen to showcase the ease of use of the developed platform for such tests and the accuracy of the measurement data is validated by comparing them with traditional measurement methods. Experimental results showed that the system can indeed be a low-cost, reliable assessment tool for performing rehabilitation assessments, especially in resource-limited settings.

While visual and spatial information plays a crucial role in Telerehabilitation, other physiological measurements, namely heart rate, breathing rate, temperature, etc., are vital in assessing the patient performance [76]. Therefore, to enhance the effectiveness of the rehabilitation session, a number of sensing modalities are considered using readily available third party sensors. These sensors are first integrated into the Telerehabilitation framework (Chapter 4) by using a customised library file, as presented in Chapter 6. Based on preliminary experiments, the chapter demonstrates the usefulness of having such additional data in a regular rehabilitation session with the help of some specific examples. Finally, the improved rehabilitation system presented in Chapter 5 is combined to complete the design of a comprehensive Telerehabilitation system, which can be potentially deployed in unstable bandwidth environments, including those areas with severe bandwidth scarcity.

The thesis concludes in Chapter 7 with a summary of the main contributions of the work presented, while realizing a comprehensive Telerehabilitation system that has the necessary intelligence to be functioning smoothly under highly inconsistent network conditions, especially under those low-speed connection environments in the developing world. Specific contribution in each phase of the work is summarised in this chapter. In concluding remarks, the author lists out the current limitations in the system and identifies specific future work directions so as to improve the developed Telerehabilitation platform so that it can be ready for potential field deployments.

Chapter 2

Basic Framework Formulation

2.1 Introduction

While technology has contributed positively towards humanity in many aspects, huge potential remains to be tapped in the area of healthcare. Medical consultation today still takes place predominantly over face to face meetings. While this is still the preferred mode of medical practice, it is not economically or socially viable and sustainable in certain situations, such as an aging population, low medical personnel to patient ratios and a general scarcity of affordable medical resources in rural areas. With the advent of computer and communication technology, simple diagnosis or follow-ups can be effectively done from home or a community focus point without the need for the physical presence of the patient in front of the doctor. Through the use of the Internet and telecommunications, medical resources can be better optimised, resulting in higher efficiency in the operations of the medical institutions as well as savings in cost, time and effort for patients.

The United Kingdom's Department of Health has launched a two-year program named Whole System Demonstrator in 2008 to explore how technology can help people manage their health independently [62]. Involving more than 6000 patients and more than 200 general practitioners, the program ran Telehealth trials on patients with medical problems such as diabetes, chronic heart failure, and chronic obstructive pulmonary diseases. The results gathered were promising, showing statistics of 45% reduction in mortality rates, 20% reduction in emergency admissions and 8% reduction in tariff costs, among others.

87% of the 195 countries in the world are developing ones, and together, they represent a huge 84% of the total global population [77]. Conversely, the healthcare spending of these countries only constitutes 11% of the total healthcare spending of the world, largely due to the lagging economies and the very low doctor-to-patient ratios. Despite lagging in general healthcare, many of these developing countries are well equipped with basic telephony and Internet access due to the introduction of telecommunication technologies. For instance, as mentioned in Chapter 1, in 2015, statistics show that 68% of the world's total number of Internet users resides in developing countries [16]. With the availability of such basic infrastructure, it is structurally viable to deploy Telehealth technology in developing countries to help bridge the gaps in medical services to the people at large and bring forth the following benefits [77]:

- Cost savings: e-consultations are about seven times cheaper than physical visits
- Easier access: rural and sub-urban populations do not need to travel to remote sites over difficult terrains for a few minutes of consultation
- Efficiency: optimise the distribution of limited medical resources to the

mass population at large.

This chapter details the development of a real-time Telehealth framework that allows doctors to diagnose or assess patients remotely with close interaction as though they are physically present in the clinic. One key requirement is to sustain the audiovisual communication which allows satisfactory diagnosis and assessment over a wide range of bandwidths. This is crucial as a consistently high bandwidth cannot be taken for granted in both developed and developing countries. Being able to operate under low bandwidth is very important, especially in developing countries, due to the limited and highly inconsistent network speed. Thus, a top challenge to be addressed in this chapter is the optimization of the usage of available bandwidth to create a low-jitter video streaming system that is capable of running under low bandwidth. It should be reiterated that the focus of this chapter is not to create another Skype-like video calling application, but to customise and optimise such a service to better meet the requirements of healthcare.

This chapter focuses directly on performance cost functions which are critical for healthcare applications through appropriate selection of existing technologies, and measured customised innovations to bridge the gaps in off-the-shelf video conferencing solutions. The framework presented in this chapter will be the base upon which subsequent works, as explained in the next chapters, are developed to build a comprehensive Telerehabilitation system.

2.2 Proposed Solution

The main requirements to be met by the proposed system are listed as follows:

- Functionality under low bandwidth: ability to work under bandwidth as low as 128 kbps
- Low jitter: ability to sustain streaming without unacceptable lag
- Reasonable frame rate: ability to maintain a reasonable frame rate of about 15 fps
- Adaptation of video quality: ability to adapt key parameters to deliver adequate video quality which is optimal under the network constraints.

To meet these requirements concurrently, the system leverages on three key functionalities not commonly associated with standard video conferencing solutions.

1. Adaptive Streaming

   In this, video quality is adjusted based on the detected bandwidth. The adjustment can be in terms of the compression rate, frame rate and resolution. In the system, the objective function maintains the frame rate at an acceptable level.

2. Dynamic Cropping using Depth Sensor

   To further reduce the image size for smoother streaming, the application makes use of the depth sensor built in Microsoft Kinect to detect the subject right in front of the camera. Depending on the range set, only the detected objects will be represented in colour image and the rest will be masked out.

3. Selective Streaming

In many situations in Telehealth, the interesting object of concern occupies only part of the full image. Thus, the system will allow the users to select only part of the video to be transmitted to the remote end and reduce file size further which is needed at low bandwidths.

2.3 System Architecture Overview

2.3.1 System Architecture

The overall system employs a distributed, connected configuration comprising of clients linked to a server over the Internet as shown in Fig.2.1.

The server is on an open connection so that it can be publicly reached with the corresponding Transport Control Protocol (TCP) port(s) unblocked. It is very common in a modern network that computers are placed behind network switches and routers, which in turn implement NAT (Network Address Translation), firewall and TCP port blocking features. NAT allows multiple computers to work behind a single router and a single IP address, but it may block some uncommon TCP ports. To counter this, some special configuration needs to be put in place, including port forwarding and firewall unblocking.

The main purpose of the server is to facilitate the connection and communication between the clients. This allows both of the clients to be mobile, and special configuration is not needed before they can connect to the server. Such a configuration is amenable to multi-party communication to be supported via the server. The configuration is also scalable to situations when the clients need to be mobile. A client-server setup further facilitates data security measures and user authentication.

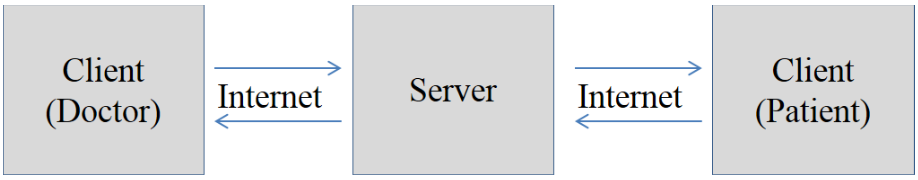


Figure 2.1: Server-client architecture

2.3.2 Hardware Setup

The hardware requirements for video streaming at the doctor's client and the patient's client are quite different. At the doctor's site, a computer equipped with a speaker, a microphone and a webcam is sufficient. At the patient's site, the Microsoft's Kinect sensor (Fig. 2.2) replaces the standard webcam to facilitate the depth extraction function [4].

During depth sensing, Kinect is able to detect the distance of the object from it using the built-in sensor. By doing this, Kinect is able to separate objects located at different distances away from it based on the depth information [78]. Kinect is also equipped with a normal RGB webcam.

2.3.3 Software Setup

Different software platforms were considered for system development. Android platform was considered first, but the limitation is that, it cannot accept external devices such as camera or audio device in case need to be included in further development stages. Another consideration was ASP.Net web development platform. In this case, image manipulation has limitations and encoding can only be done at server side. Third consideration was Microsoft .Net windows application development platform. This has the advantage of image manipulation as well as ability to accept multiple devices for future improvement as well

Figure 2.2: Kinect sensor [4]

as ease of use. Due to the wide acceptance and usage of its windows platform, it was chosen for final application development using Microsoft Visual Studio.

The system runs on two programs, one for the clients and one for the server. All the programs are written using C# language running on WPF (Windows Presentation Foundation) technology of the .Net Framework. The high-level nature of C# language means that many of the low-level technical issues have been addressed. Also, the WPF technology better facilitates the development of user interface [79].

2.4 Video and Audio Processing

2.4.1 Camera and Image Processing

Since the client program works with two types of cameras, it interfaces with them differently according to the camera type. For Kinect, the official Kinect for Windows SDK is used while DirectShowNet [80] open-source library is utilised for communicating with a normal webcam. Another open-source library used is WriteableBitmapEx [81], which is capable of doing per-pixel manipulation.

2.4.1.1 Kinect

Kinect for Windows SDK supports two ways of getting image data from Kinect; event-based and polling-based method [82]. In the proposed system, polling is used to better control the frame rate whereby a timer will be activated at a fixed interval to obtain the next frame in the stream (maximum of 30 frames per second). Data returned from the colour stream are available in either YUV or RGB format, RGB is chosen due to its simplicity. Depth stream data are returned in a different format from the colour data. Instead of an RGB byte array, depth stream returns a byte array in which each pixel contains the distance from the camera to the objects within the camera's field-of-view. Each pixel in the depth stream is represented by 16 bits to store the distance information. To convert the 16-bit depth data into millimetre, the following formula is used [83]. Assuming P_i represents a 16-bit depth data at a particular pixel, the distance, D_i can be calculated using Eqn. 2.1, where $>>$ denotes the logical right shift operation.

$$D_i = P_i >> 3 \tag{2.1}$$

2.4.1.2 Webcam

On Windows platform, the most common way to access media devices (including webcams) is through the use of DirectShow framework [84]. The main building block for DirectShow is the filter [85] which is simply a component that receives input and produces output in a specific form. In the proposed system, the filters involved are Video Input filter for getting data from the video input (webcam) and Sample Grabber filter for obtaining individual samples from the video source.

2.4.1.3 Image Processing

After obtaining the images in raw format the program processes them to be suitable for transporting over the network. There are three main steps involved; cropping, scaling and encoding. The cropping selection is carried out explicitly by the user by drawing and placing a rectangular window over the interested part of the image. The program controls the crop area such that the selection is always within the image itself. Assuming the original image has leftmost corner position at (X_1, Y_1) and has width and height (W_1, H_1) while the selection has corresponding parameters of (X_2, Y_2) and (W_2, H_2), the program ensures the following conditions:

$$X_1 \leq X_2 \leq X_1 + W_1 \tag{2.2}$$

$$Y_1 \leq Y_2 \leq Y_1 + H_1 \tag{2.3}$$

$$W_2 \leq W_1 + X_1 - X_2 \tag{2.4}$$

$$H_2 \leq H_1 + Y_1 - Y_2 \tag{2.5}$$

Scaling is done to scale down the images to smaller sizes. In this work, three scaling factors are used; 1.0, 0.5, and 0.25. The final step of the manipulation is to encode the cropped and scaled image before sending to the remote end. Motion-JPEG codec is invoked in the system using the built-in .Net API. The scaling factor and the compression rate are both determined based on the upstream bandwidth of the client.

2.4.2 Audio Recording and Playback

Other than video, the audio component is also a crucial part of the system. Two open-source libraries are used, namely NAudio [86] and NSpeex [87]. NAudio is used to record and playback audio data while NSpeex is used to encode and decode the audio data. Speex is an open-source audio codec specifically designed for speech. Speex supports compression in three bands; narrowband (8kHz), wideband (16 kHz) and ultra-wideband (32 kHz) [87]. Narrowband is used here to conserve bandwidth.

2.5 Data Transfer

Once the audio/video data is acquired and processed, it will be transferred over to the server, which in turn sends the data to the other connected client. The system uses TCP as the transport layer protocol.

2.5.1 Server Program and Client Program

The server program is a C# console program. The server program actively listens on ports 8826, 8827 and 8828 for incoming video, audio and text message streams respectively. Upon receiving data from one end, the server loops through the connection list to see if there is any connected client on the other end. If so, the server continues to transmit data over to the available client.

To communicate with the other client on the remote end, a client first connects to the server through the three ports and continues to send data over the corresponding connection upon establishment. For transmission of video images, the sending client maintains a timer that fires every 67 milliseconds ($\approx 15fps$) to send video data. Transmission of audio is similar to that of video while that of text data happens on demand as and when users input data.

2.5.2 Bandwidth Detection Algorithm

One of the main features this system offers above standard teleconferencing programs is the ability to adjust the video quality according to upstream bandwidth. The bandwidth detection happens in every 2 minutes once the client establishes server connection. To measure the upstream bandwidth, a client first sends a packet to the server and keeps track of the sent time. Upon receiving the complete packet, the server then acknowledges the receipt of the packet by sending a small acknowledge packet. Assuming 200kB (204,800 B) packet is sent from the client at time T_1 and the acknowledge packet is received from the server at time T_2, the bandwidth, B_w in bytes per second, of the client's upstream can be estimated as:

$$B_w = \frac{204800}{(T_2 - T_1)} \times 80\% \tag{2.6}$$

Note that only 80% of the detected bandwidth is used to ensure that the video data does not congest the network, while leaving the allowance for unexpected situations. After the bandwidth has been estimated, it is matched with a list of common network connection speeds to determine the transmission capacity

Table 2.1: Allowable bytes in 1 second for different network speeds

Network speed, B (kbps)	**Bytes per second,** X = B*1024/8	**Allowable bytes in 1 second,** B_s = 0.8X	**Allowable bytes in 1 frame,** B_f = B_s / 15
128	16384	13107	873
256	32768	26214	1747
384	49152	39321	2621
512	65536	52428	3495
768	98304	78643	5242
1024	131072	104857	6990

on hand and the corresponding video quality to employ. Table 2.1 shows the allowable bytes per second for different network speeds, B_s, to be matched to the measured capacity, B_w. The first column is the list of common network connection speeds and the third column shows B_s, the allowable number of 'bytes' per second, which is 80% of the total bytes per second. The allowable number of bytes per frame, B_f, is calculated on the basis of the assumption that the frame rate requirement to maintain is 15 fps.

2.5.3 Choosing the Image Quality for Streaming

Detecting the bandwidth is only the first step for smooth streaming of the video. The next step is to decide the desired corresponding compression rate and resolution such that the frame rate requirement of 15 fps can be maintained. As mentioned earlier, how much data can fit into each of the 15 frames at different network speeds is already calculated (B_f) as shown in the last column of Table 2.1.

Now that B_f is determined, the final step is to determine the JPEG file size at different compression quality and scaling factor that can fit snugly into the allowable bytes space. However, the JPEG file size cannot be determined directly from the compression rate and resolution, as the file size is determined only after the image has been encoded, and it would differ between image to image. To this end, an empirical approach is used to set up a lookup table by running multiple tests on different pairing of compression quality (10 to 65) and scaling factor (0.25, 0.5 or 1.0) of images selected to be representative of those to be transmitted during the actual application. The raw image of a simulated consultation session is saved in bmp format (with same frame resolution as the Kinect/ webcam) for this purpose and compression is directly applied to the raw image. The key idea is to fit video data of the highest, sustainable quality that just fall within the file size constraints as shown in the last column of Table 2.1. For example, assuming the network speed is B kbps that allows B_f bytes per frame, and that there are two sets of data in the form of (file size, compression quality, scaling factor), which are (S_1, F_1, Q_1) and (S_2, F_2, Q_2) with the condition $S_1 \approx S_2 < B_f$, $F_1 \geq F_2$, $Q_1 \geq Q_2$, the combination (F_1, Q_1) is chosen over the other set. In short, after carrying out a set of compressions, the highest possible values for the compression quality and scaling factor are considered and selected as long as the compressed image is lesser than the allowable size per frame. The scaling factor was given the priority while selecting the parameters and only when the image quality dropped to unacceptable levels, the scaling factor was reduced to 0.25. The lookup table is thus constructed as shown in Table 2.2.

Note that in the look-up table, there is no combination of compression quality and scaling factor that can fit into the allowable bytes for network speed of 128 kbps. Thus, to still achieve the frame rate of 15 fps here, the program has to go beyond the 80% network capacity, and evoke bandwidth conservation measures

Table 2.2: Compression Quality and Scaling Factor for different network speeds

Network speed, B (kbps)	**Allowable bytes in 1 frame,** B_f	**Compression Quality**	**Scaling Factor**
128	873	N/A	N/A
256	1747	12	0.25
384	2621	35	0.25
512	3495	60	0.25
768	5242	23	0.5
1024	6990	35	0.5

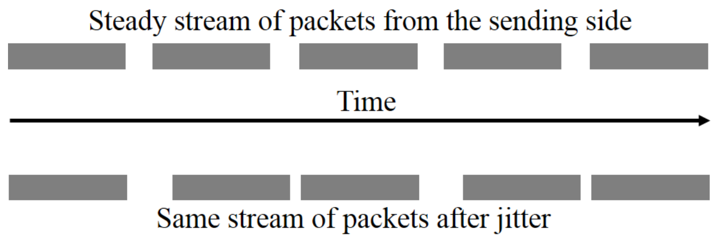


Figure 2.3: Jitter effect

of depth sensing and selective cropping.

2.5.4 Jitter and De-jitter Buffer

Although the audio and video packets are sent at fixed interval at the sending side, the same series of packets may arrive at the receiving side with jitter. Jitter represents the deviation from the true periodicity of an assumed periodic signal. Figure 2.3 shows how a smooth periodic series of packets on the sending sides becomes a non-periodic series at the receiving side.

The phenomenon of jitter can result in jerky and unsmooth motion in the video stream or noise in the audio stream received. A common workaround this problem is by using a de-jitter buffer, which is a fixed size buffer that queues the incoming packets. As larger buffer can lead to higher latency, it is designed to be large enough for de-jittering so as not to introduce lag. In this system, the de-jitter buffer for video stream is 3 frames while that of the audio stream

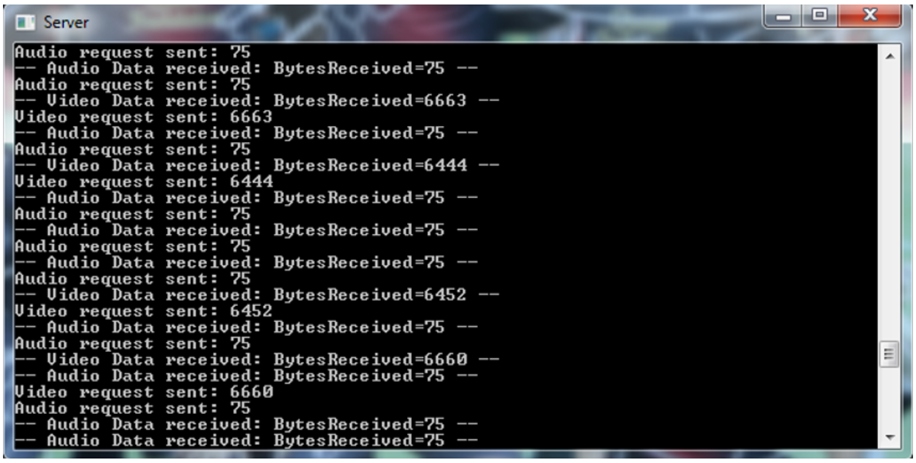


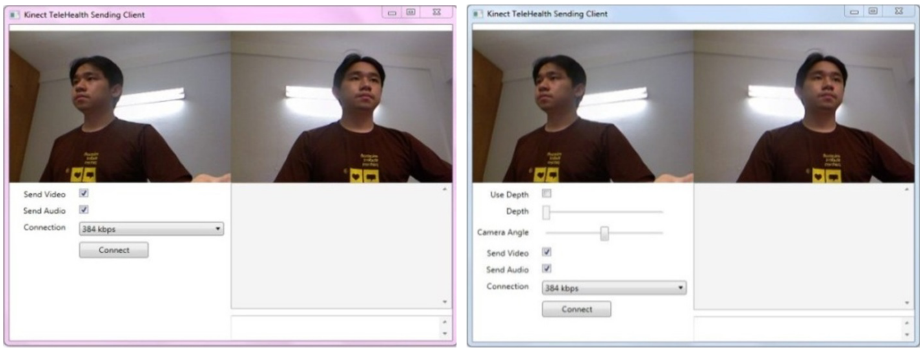
Figure 2.4: Server console program

is 30ms. These parameters are determined empirically.

2.6 Main Results

Key screenshots of the client and server programs are first presented to give an overall picture of the system operations. Figure 2.4 shows the server console program that is responsible for facilitating communication between two clients. Figure 2.5 shows the main window of the doctor's and patient's clients. There is also a text message panel at the bottom right of the client window, allowing the conservation of bandwidth using text in lieu of audio conversation.

Figure 2.6 shows the dynamic cropping feature that is available on the client programs. Depth sensor built in the Kinect is used to achieve this. Figure 2.7 shows the manual cropping feature that is available in the client program. Only the cropped part is sent over the network to reduce data size. The most important quality factor of concern in this system is the frame rate of the video and the key objective function is thus to maintain a frame rate of 15 fps at various connection speeds for satisfactory smooth video rendering.



(a) doctor's client (b) patient's client

Figure 2.5: Client program windows

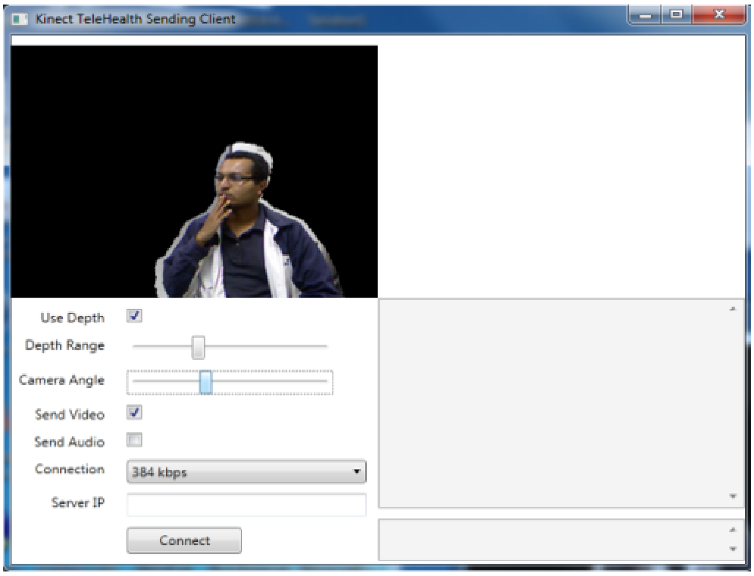
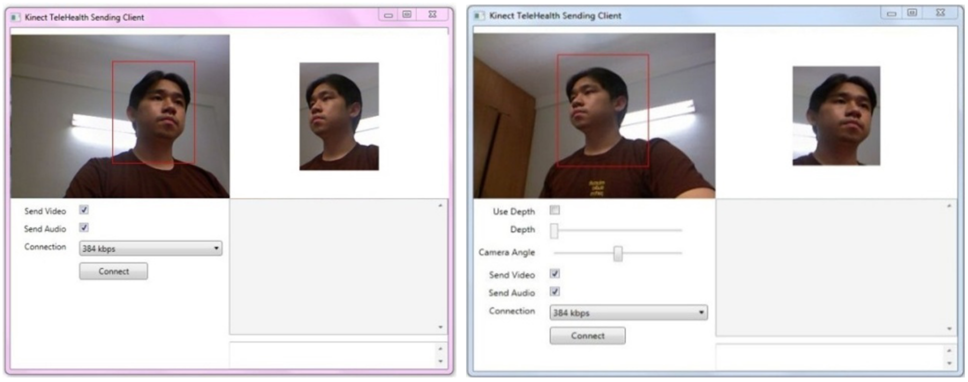


Figure 2.6: Video with depth sensing turned on

2.6.1 Analysis Environment and Methodology

Since each of the received frames is in the form of JPEG image, it is easy to measure the frame rate as each received image represents a frame. To measure the frame rate, the receiving client program is launched in the debug mode with a modified programming code. At the place where the program is periodically getting the next frame from the de-jitter buffer, the code is injected to check and record whether the buffer is empty. If it is empty, a frame is said to be dropped. By examining 1000 frames for each connection speeds, the ratio of the dropped



(a) doctor's client (b) patient's client

Figure 2.7: Cropped video during a consultation session

packet versus total packet is then calculated.

2.6.2 Streaming Results

Table 2.3 shows the streaming quality in terms of frame rate at each network speed. Each entry is examined over the duration of 1000 frames for the total number of dropped frames, and the frame drop ratio was tabulated. Full 15 fps is not achieved due to excessive jitter in the network during the experiments causing frame drop in de-jitter buffer. However, this is an acceptable frame rate for humans to create the sensation of visual continuity as reported in several studies in the past [88] [89] [90]. Note that at 128 kbps however, the frame rate falls below 13. As explained previously, cropping and depth-sensing features should be invoked here to bring up the frame rate to the required level.

2.6.3 Comparison with Skype

Although the design of this system is guided by a set of requirements different from those for commercially available applications, Skype is used for a comparison study to evaluate the relative performance at low bandwidths. Since

Table 2.3: Frame drop ratio for different network speeds

Network speed, B (kbps)	**Total received packets,** P_t	**Total dropped packets,** P_d	P_d / P_t **ratio,** F_d	**Average frame rate,** F_r=(1-F_d)x15
128	1000	165	0.165	12.52
256	1000	76	0.076	13.86
384	1000	105	0.105	13.43
512	1000	93	0.093	13.60
768	1000	111	0.111	13.34
1024	1000	118	0.118	13.23

Skype is a proprietary program, there is no rigorous way to compare with it. Thus, the comparison is done using the following method. A video conferencing session using Skype is recorded. At the patient's end, a short clip running at 15 fps, looping a sequence of numbers from 1 to 15 in each frame, is captured by the camera (refer here for clip: $http://bit.ly/1WiWYX7$). At the doctor's end, the video is received and recorded while limiting the bandwidth to 128 kbps.

The clip is recorded for three minutes and subsequently analysed by choosing 10 random instants of one second duration from the recording. At each time instant, the frame rate is observed to see if all numbers (1 to 15) are displayed. Since each number takes up a frame, the count of numbers appearing over one second is equivalent to the frame rate. The results in Table 2.4 show that the median frame rate for Skype's at 128 kbps is about 8 fps. Comparing to 13 fps achieved with this system, the results obtained show that this system can perform better than Skype in terms of frame rate alone at low bandwidth.

However, no conclusion is drawn that Skype is overall a poorer general solution for video streaming. In fact, Skype strives to maintain a very high video quality (in terms of resolution) even at 128 kbps, thus resulting in network congestion. This system is able to circumvent that by lowering quality and scaling

Table 2.4: Skype frame rate

Time point	**Frames displayed**
1	10
2	8
3	10
4	7
5	10
6	8
7	7
8	8
9	10
10	7

rate in response to the bandwidth via a delicate balancing act in a zero sum game in favour of the Telehealth purpose.

2.7 Summary

In this chapter, a system that is similar to standard teleconferencing applications, but has customised and optimised features for Telehealth usage, is designed and implemented. Through the use of features such as adaptive video quality, selective streaming via video cropping and depth sensing, this system is able to facilitate Telehealth sessions between doctors and clients while maintaining an acceptable video quality of around 15 fps. This basic communication framework presented here will be used in this thesis to implement further works and develop the solution towards a comprehensive Telerehabilitation system.

However, sending spatial information that is crucial for understanding the patients movement is still challenging under constrained network conditions. In Chapter 3, Kinect's capabilities for spatial data extraction and skeleton detection are further explored and its possibilities for being used in place of larger data consuming stereoscopic image capturing mechanisms (including 3D technology), especially in bandwidth limited settings, is studied. The chapter also presents information on using Kinect for rehabilitation assessments and to calculate body movement parameters like distance, velocity, angle of motion, etc. using the extracted depth data and experiment results are presented to verify the system performance.

Chapter 3

Depth Data Extraction and Processing with Kinect

3.1 Introduction

Two-dimensional (2D) video-based medical consultation has been explored widely in past 15-20 years. 2D tele-video has been demonstrated to be acceptable for face-to-face consultation supplementing telephone, and useful for visual examination of wounds, abrasions, etc. [63]. However, certain clinical examinations necessitate the use of three-dimensional (3D) video for accurate assessment of the patient's condition. One such scenario, as discussed by Hoenig et al. [64], is gait assessment. A 2D video from the frontal view was not sufficient to reliably assess foot placement while walking. Simply having the patient turn sideways was able to compensate for a single lens camera when measuring cane height. However, this may not be feasible for gait assessment which typically requires a minimum distance of 3 metres for standardised measures of gait and balance

[91].

One way to overcome this issue is by transmitting stereoscopic images and processing the images in order to render a 3D reconstructed video at the receiver using special algorithms. Welch et al. used similar techniques for rendering high quality 3D video from a remote location using multiple cameras in an application named 3D medical consultation or 3DMC [63]. In their prototype, a small array of cameras is used to reconstruct a real-time online 3D computer model of the real environment and events. But the challenge in implementing such a system is the high amount of data incurred while operating over bandwidth-limited networks. Sending of 3D videos at network speeds of 128 kbps is almost an impossible task to achieve. According to experiments conducted by Russell et al. [65] who studied the insufficiency of single 2D camera in gait assessment, two cameras with both frontal and lateral views can fulfil the spatial resolution requirement. While Russell et al. also showed this method can work with low bandwidth Internet transmission, it nonetheless required a huge data payload.

Another alternative is to use the 2D-plus-Depth (also known as 2D +Z) technology, a stereoscopic video coding format that is used for 3D displays, developed by Philips [66]. Each 2D frame is supplemented with a depth map captured using a Time-Of-Flight sensor. This depth map is a greyscale map with white indicating the pixel in front of the display and black indicating the pixel in the background. This has the advantage that it takes only 5-20% more bandwidth than 2D images [92]. However, a disadvantage is the limited amount of depth displayed using 8 bit greyscale. Moreover, creating accurate 2D-plus-Depth videos is generally costly and difficult, and the depth cannot be reliably estimated in monocular video in most cases. It also needs special software to do the conversion in live mode [93]. There are some systems developed for rehabilitation purposes using Kinect technology [94][95], but these are mainly for in-house rehabilitation programmes and they do not specifically address the issue of information transfer over low bandwidth networks.

In situations where the rendering of complete 3D video is impractical, transferring spatial data for only specific features can be considered. This chapter, written as an add on to the framework presented in Chapter 2, introduces an innovative way of utilising the depth information of selected objects in the image together with the usual 2D video, thus achieving some degree of spatial resolution for Telerehabilitation applications. A Microsoft Kinect sensor is used together with an open source colour detection and tracking library package in order to extract the desired depth data from the image. The extracted depth data is then plotted on a graph and displayed alongside the images in order to make sensible conclusions about the patient's condition. Only a few extra bytes are needed to represent the depth data and hence it does not induce any significant load over the existing 2D video transmission. In this chapter, examples of Telerehabilitation assessment, where spatial resolution is required, will be highlighted and solutions leveraging on the proposed approach will be presented to show the effectiveness of such approaches.

3.2 Methodology

3.2.1 Hardware & Software

The main hardware used in the development of this framework is the Microsoft Kinect sensor with the Software Development Kit (SDK) for Kinect installed in a Windows 7 computer. An assessment room of at least 3 metres in width and length was required to carry out some of the assessments of Telerehabilitation. As the work in this chapter is built on the basic framework developed in Chapter 2, the programming was also done in Visual Studio 2010 on the Windows Presentation Foundation (WPF) platform using C# language. Kinect's skeleton stream was used for tracking specific body parts when required.

Colour detection part of the work is carried out based on AForge.Net [96], an open source library developed for C#.Net framework, and uses different kinds of colour filters in order to achieve the purpose. The extracted depth information is presented on a dynamic graph panel as a line graph. This graph is embedded in the program using Dynamic Data Display (D3) [97], an open source project owned by Microsoft Research. D3 is a way of visualising a dynamic data set in the WPF application in the form of a line graph, bar chart, etc. Zooming and panning are already embedded into this library and this helps in obtaining a closer look at the data for deeper analysis. This library also has embedded functions to copy and save the plotted graph to the hard disk for future reference.

3.2.2 Depth Extraction Based on Colour

As mentioned earlier, the AForge.Net open source library is used for colour tracking. There are multiple image processing filters which allow filtering of pixels depending on their colour values. These filters may be used to determine if the specified colour is detected in the displayed image frame. For example, ChannelFiltering filter filters the RGB values of pixels inside/outside of specific range operating in RGB colour space. Another filter named HSLFiltering filter operates in HSL (Hue, Saturation, Luminance) colour space and filters those pixels inside a specified range and keeps out the rest of the pixels. In this work, EuclideanFiltering filter is used due to its effectiveness and short processing time while operating in the performance test environment. This filter filters those pixels inside of the RGB sphere with a specified centre and radius, and fills the rest with a specified colour.

This filter is applied to Kinect's colour image stream for object detection. The colour image frame from Kinect's colour stream is initially converted to a bitmap image format. This bitmap image is then passed to another method together with the selected colour to run the colour detection algorithm based on the filter described above. Once the specified colour is detected, the biggest single object with the specific colour is identified through an iterative algorithm which loops through all the objects inside the image, and a rectangle is drawn around that object. The centre of the rectangle is then calculated and a small circle is drawn as well for the user to identify the point of focus. The X and Y coordinates of this point will be used to identify the distance of the object from the Kinect sensor. The new image with the rectangle will be converted to a bitmap source object in order to display on the screen. This same image is sent to the receiver after going through appropriate encoding algorithms.

Kinect sensor has a depth stream as well, which stores the distance data of each pixel on the camera's field-of-view in a 16 bit array format of short integers. A 0 value denotes that no data is available at the pixel either because the object is too close or too far from the camera. The detectable range of the Kinect sensor is from 0.4 metres to 4 metres. This depth information is stored in a specific location corresponding to each pixel's coordinates in the depth image frame. For example, if X and Y are the coordinate information of the specific pixel in an image frame, the corresponding depth information for that point will be stored at the location given by Eqn. 3.1, with w being the width of the depth frame.

$$[X + (Y \times w)] \tag{3.1}$$

Similar to what is mentioned in Chapter 2 Eqn. 2.1, out of the 16 bits used to represent the depth, only the last 13 are used to represent the distance. So this depth information can be converted to distance in millimetres by doing a right shift operation, as in Eq. 2.1.

Using Eqn. 2.1 and 3.1, and the coordinates of the centre of object calculated by matching the depth image frame and the colour frame, the distance of the coloured object from the Kinect can be extracted. This information is later sent to the line graph using D3. This plot will contain the detected depth in the Y-axis and the data point number on the X-axis. By observing the graph, one can tell how far the object is located from the Kinect sensor along the Z-axis.

3.2.3 Depth Extraction Based on Skeleton

The ability to extract and track the positions of the human body is another function of the Kinect. Other than the RGB image stream and the depth stream, the Kinect sensor also has a skeleton stream which can detect twenty joints of the skeleton, including the head, hip, knee, ankle, etc. In some Telerehabilitation exercises where a full human skeleton has to be visible on screen, the skeleton stream from Kinect can be utilised to detect certain body positions and assess whether the patient is performing the exercise in the right way.

There are two modes in skeleton tracking: seated mode and default. Default mode, also known as standing mode, tracks all the twenty skeletal joints whereas the seated mode only tracks the 10 upper-body joints including shoulders, elbows, wrists, arm and head. The default mode detects the user based on the distance of the subject from the background and the seated mode uses movement to detect the user and distinguish him or her from the background such as a chair or couch [98]. In cases where the patients suffer from lower body paralysis, default mode is recommended since the rehabilitation focus will be on the lower body joints and seated mode will only capture upper body joints. Thus, different tracking modes are used in this framework based on the consultation requirements.

Depth range can be set to either near mode or default mode. In the near mode, skeletal tracking returns position-only tracked skeletons without the possibility of getting the full skeletal joint positions, from as close to the sensor as 0.4 metres up to a maximum of 3 metres. Although both seated and default modes are usable in the near range mode, the seated mode is more commonly used since in this mode, the whole skeleton does not need to be tracked. In default depth range, the tracking position can be from 0.8 metres to 4 metres. Again, the depth range is chosen based on the application requirement in this framework [98].

Kinect sensors default setting enables it to track multiple skeletons in the frame simultaneously. As a result, the tracking algorithm may end up altering between the joint measurements from different skeletons. This is indeed a challenge and may lead to inaccurate measurements, especially when the patient undergoing rehabilitation needs to be assisted by a caregiver who is going to be positioned close to the patient. However, there is a workaround implemented in the developed program to overcome this challenge. In the Software Development Kit (SDK) mentioned earlier, there is a method to enable the program to select and track the nearest skeleton to the Kinect. This method is used in the program so that it ensures that as long as the patient is positioned nearest to the Kinect, with the caregiver assisting from behind, the program is able to select the correct joint to be tracked without fail. This has been verified through multiple trials with multiple people in the frame and the program was indeed able to track the most prominent skeleton that was nearest to the Kinect without any issue. When the system is eventually deployed in real-life scenarios, user education should include this so that they are aware of the limitation beforehand.

Similar to the case of colour based detection, the colour image frame from the colour stream is converted to a bitmap image format. This is for editing of the frame with the identified joint later on. Once an active skeleton is detected using the skeleton stream, the program will identify the specified joints on the detected skeleton. This skeleton point will be marked with a filled red ellipse using a separate method. The new bitmap image with the ellipses drawn will be converted to a bitmap source as in the previous case and sent to the receiver after passing through appropriate encoding algorithms. The depth of the detected joint can be directly extracted using the SDK commands. This value, in metres, has to be multiplied by 1000 in order to convert it into millimetres.

3.2.4 Velocity Extraction from Joints

Other motion parameters can be derived from the coordinate positions of the joints in the skeleton. By making use of this information, it is possible to measure a motion parameter such as the velocity of a specified joint while the patient performs the exercise. For example, consider the case of walking assessment with the use of skeleton stream by tracking the hip joint position of the patient. The patient walks along a straight line and the physician assesses his deviation from the straight line as well as his walking speed.

Let the hip position coordinates at time=t_1 be at (x_1, y_1, z_1) and at time=t_2 be at (x_2, y_2, z_2). Velocity is the time derivative of position and by using this analogy, the absolute velocity of the hip joint between t_1 and t_2 can be calculated as shown in Eqn. 3.2.

$$|v| = \frac{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}}{(t_2 - t_1)} \tag{3.2}$$

This estimated value of velocity will be in metre/second since the coordinate values are measured in terms of millimetres and the time in terms of milliseconds. The interval between t_1 and t_2 is chosen to be of 20 data points. If it is too short, slow movements cannot be measured as the velocity will be close to zero value. If it is too long, fast movements will not be measured well. The sampling rate of 20 data points translates to between 1 to 2 seconds in the time scale. From repeated trials, this value was found to be more ideal for measuring velocity in most of the exercises carried out by patients. This method is used to measure the velocity of body joints in other exercises throughout this thesis as well.

In addition to the absolute velocity calculation, individual velocity components are calculated as well in order to understand the velocity of motion along each direction. The below equations are formulated based on the fundamental principle that velocity is calculated from the rate of change of position. Thus the rate of change of position in each direction (x, y, and z) is calculated as:

$$v_x = \frac{(x_2 - x_1)}{(t_2 - t_1)} \tag{3.3}$$

$$v_y = \frac{(y_2 - y_1)}{(t_2 - t_1)} \tag{3.4}$$

$$v_z = \frac{(z_2 - z_1)}{(t_2 - t_1)} \tag{3.5}$$

Calculating individual velocity along each axis while carrying out specific exercises (for example lifting a load while stretching arms) can assist in identifying the direction of the movement as well as the direction in which the movement is the weakest and thus improve rehabilitation assessment. Absolute velocity alone would not have been sufficient for such a purpose.

The skeletal joint information can be adjusted across different frames to minimise jittering and to stabilise the joint positions, thus making the calculation of velocity more accurate. A smoothing mechanism is provided by Kinect SDK, which is based on Holt Double Exponential Smoothing method [99]. Skeleton stream is enabled with this smoothing filter which filters out small jitters with minimum latency. This filter can be controlled using five parameters such as Smoothing, Correction, Prediction, JitterRadius and MaxDeviationRadius [100]. Smoothing parameter must be in the range of 0 to 1 and increasing the value leads to higher-smoothed skeleton positions. As the value increases, the responsiveness decreases. The correction parameter must also be in the range of 0 to 1. Lower values result in slower response to correction towards the raw data and greater smoothing. Prediction refers to the number of frames predicted into the future and the value must be greater than or equal to zero. For this parameter, values greater than 0.5 may lead to overshooting when the joints move quickly. JitterRadius is the radius in metres for jitter reduction. MaxDeviationRadius is the maximum radius in metres that the filtered positions are allowed to deviate from the raw data. These values are chosen such that there was little latency incurred by the filter while small jitters were effectively filtered out [100].

3.2.5 Calculation of Angle between Joints

The coordinate information for each joint can be used for calculating the angle between them. For example, if the coordinate data for right wrist, right elbow and right shoulder is known, the angle between the upper and lower arm with elbow as centre point can be calculated using vector manipulation. To achieve this, a vector is formed from right elbow to right wrist (let it be A) and another vector is formed from right elbow to right shoulder (let it be B) using vector calculation using the corresponding coordinate data for each joint. The angle between the two vectors can be measured using:

$$Cos\theta = \frac{A \cdot B}{|A||B|} \tag{3.6}$$

The numerator in Eqn. 3.6 is the dot product of the two vectors and the denominator is the product of their magnitudes. Such calculations can be used to assess the patient's exercise pattern (e.g. lifting a load with the right hand) so that the physician can observe whether the change in angle is uniform throughout the lifting process and potentially identify the position at which the hand is weaker or stronger during the exercise.

3.3 Experiments and Results

A few common assessment scenarios will be used in this section to leverage on the tracking and representation of depth data of specific body parts or objects. Test runs were conducted on these scenarios using the methods explained earlier and the data obtained is represented in line graphs. Tests were categorised as cases which tracked one mobile object, one mobile and one fixed object, two mobile objects, multiple joints of the human skeleton, and the velocity& angle of joint movements. This section provides the details of the test runs and analysis of the collected data.

3.3.1 Tracking of Single Mobile Object

In this test, a single mobile object is tracked based on user-specified colour. One possible area of application is the assessment of the walking posture of a patient. In a normal 2D video, it would not be possible for the physician to see if the patient is walking in a straight line and at the same assess the body posture of the subject by looking from a lateral view or a frontal view alone. This spatial resolution framework can be useful in such an application by tracking the depth information of the subject's body while he carries out the exercise.

The Kinect, placed on a table top as parallel to the ground as possible, will give feedback on the patient's position based on the colour tracking of the patient's jacket/shirt. The subject was asked to walk along a straight line of 2.15 metres as parallel to the Kinect as possible. Figure 3.1 shows the above mentioned scenario. The user can select the specific colour to be tracked on the screen. In this case, the subject's jacket colour is selected. The program draws a rectangle around the captured object and a circle to mark the point of measurement. The returned depth data from the Kinect is plotted on a line graph on the right. The X-axis represents the data point number, whereas the Y-axis is the measured depth in millimetre.

A moving average is calculated based on the previous 100 measured points and plotted along the measured values in order to assist in the assessment. A "first-in, first-out" (FIFO) queue is used to achieve this function. Once the first 100 points are available, a new loop starts to operate which will calculate the average of the available data. The newly arrived data will push the most dated data out of the queue and the average is calculated again. This process is continuous. Programming logic for the above mentioned algorithm is drawn in Fig.3.2. This average plot will assist the physician in determining how much the patient has deviated from the straight line while carrying out the designated exercise as well as understand the underlying trend of the plotted data.

Based on the projected data line, the physician can determine if the exercise

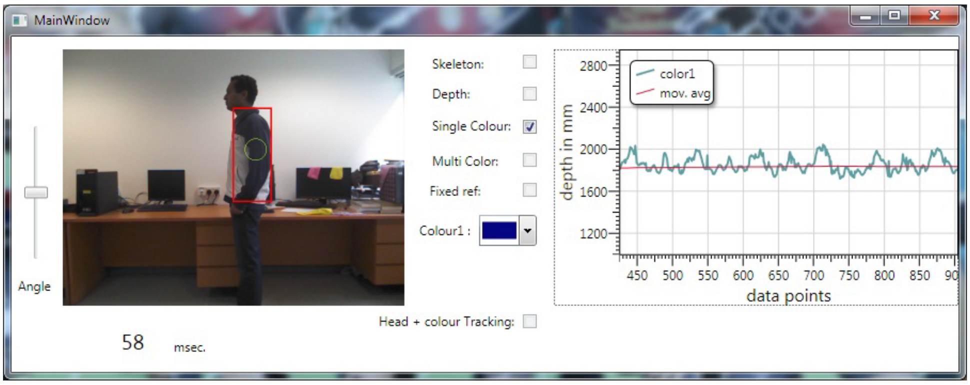


Figure 3.1: Single object tracking program screen

was performed correctly. For example, the depth data within a certain range from the average line implies that the walk was along a straight line, whereas a wide data fluctuation implies that the walk was in a zigzag line. Two separate trials were recorded and plotted on Figure 3.3. "Good" represents a patient walking on the line and "Bad" represents a patient walking on zigzag line. The colour tracking method is used instead of a skeleton based approach in this example, since the full human skeleton may not be necessarily visible at all times in this scenario.

Measurement error of Kinect's depth sensor was determined to be 2mm at 1meter depth and 2.5cm at 3 metres depth according to a study conducted by Khoshelham and Elberink [101]. In this exercise the patient was 2 metres away from Kinect which meant that the measurement accuracy was within 1-2 cm and the Kinect was still able to detect movements outside this range accurately. This suggests that the assessment performed in this case was reliable.

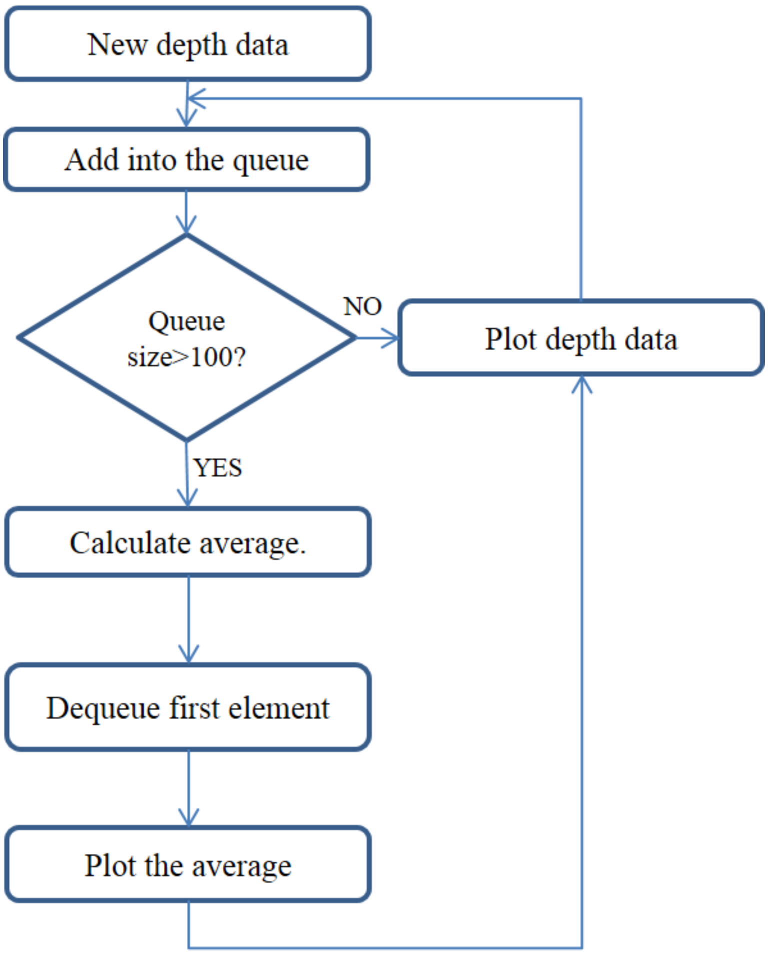
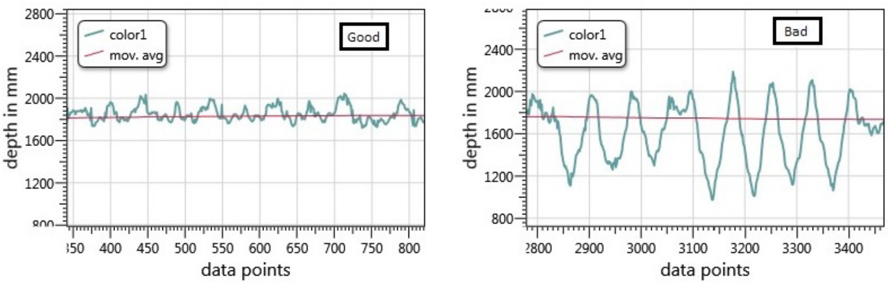


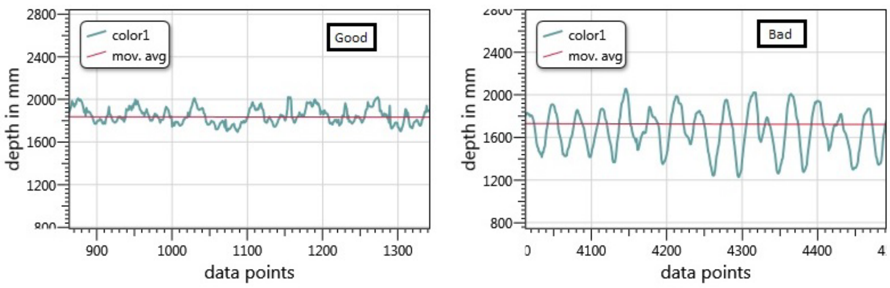
Figure 3.2: Programming algorithm for moving average calculation

3.3.2 Tracking of Single Mobile Object with reference to a Fixed Object

In this case, there were two objects being tracked, a fixed object and a mobile object. To select the fixed object, the user has to click a mouse over the object and a red circle will be drawn around the selected point. The depth of this object is then calculated based on the coordinate values of this position as explained in the previous section. The mobile object is chosen based on colour as in the previous case. In this case, the subject is asked to perform a simulation of drinking water from a cup. The subject's head is chosen as the fixed position and the yellow coloured cup is selected as the mobile object.



(a) first trial



(b) second trial

Figure 3.3: Results of walking posture analysis

Figure 3.4 shows the experiment set-up in the program window. Both the returned depth data are plotted on the graph on the right. From the line graph plot, the physician can see how consistently the exercise was performed by the subject by comparing both plotted lines. Fig.3.5 shows a magnified image of the graph plot for further analysis by the physician if necessary. If the cup is closer to the mouth, both lines will be close and vice versa. Analysing the graph carefully can reveal data, such as how many cycles were done by the patient in a particular time window and can even be used as a gauge to measure the patient's progress over multiple sessions of Telerehabilitation.

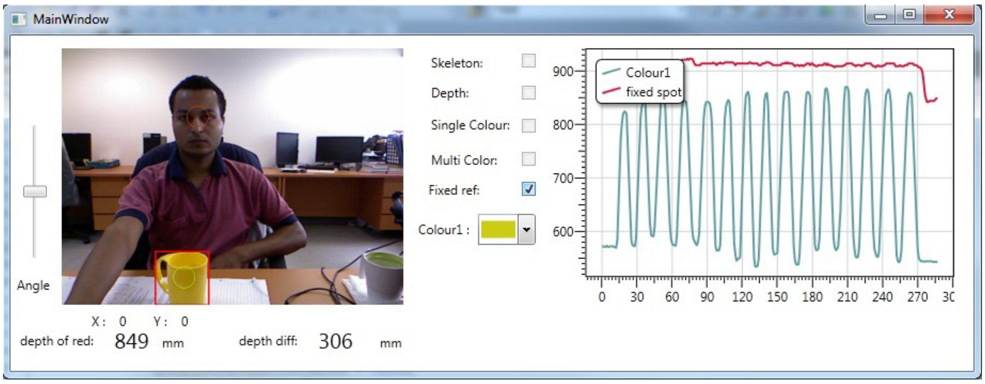


Figure 3.4: Single mobile object with fixed object tracking program screen

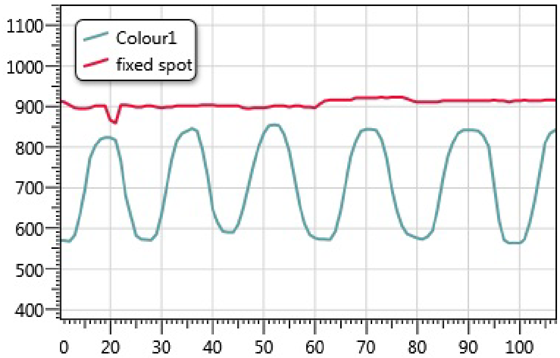


Figure 3.5: Magnified results of the drinking simulation exercise

3.3.3 Tracking of Single Mobile Object with reference to a Moving Body Part

One drawback with the method of selecting a body part as a fixed object is that once the body part moves, the reference depth is changed although it may not affect the final assessment of the exercise. Another drawback is that if any other object is brought to the front and blocks the selected point, the new object's depth will be captured. In order to overcome this limitation, there are two ways proposed. One is to track a body part based on skeleton stream from the Kinect. Another way is to track based on the colour of the fixed object. The former method is explored in detail here and the latter method will be explained in the next case.

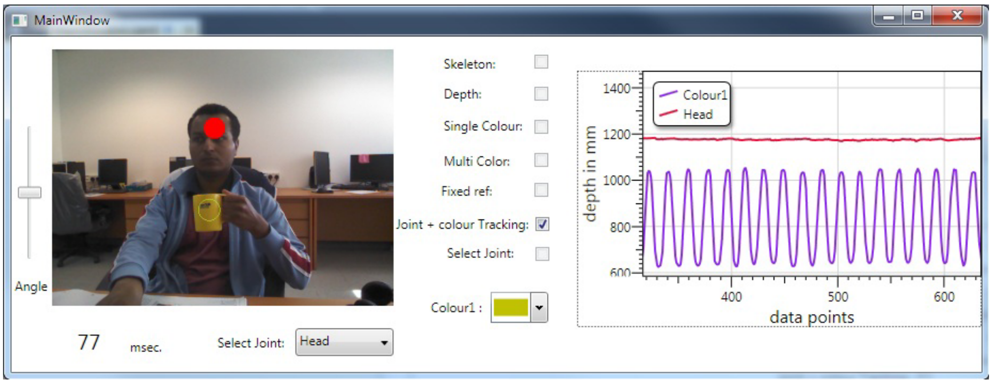


Figure 3.6: Tracking of head position together with the mobile object

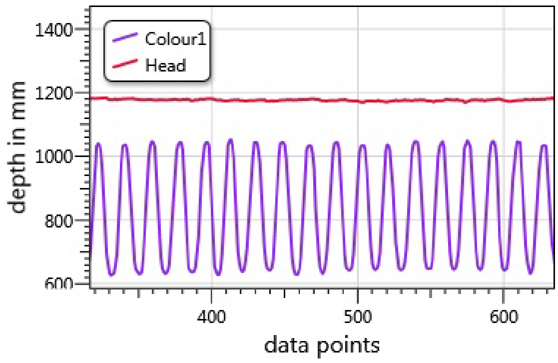


Figure 3.7: Enlarged image of the plotted data for analysis

In the previous exercise, the subject's body part tracked was the subject's head position. Thus, Kinect's skeletal stream was activated to track the head in this case. Since the full body skeleton was not visible to Kinect in this case, the 'Seated' mode was activated with the depth range set to 'Near'. Once the upper body was visible to Kinect, the selected body part was tracked and marked by a filled red ellipse, head in this case. The other mobile object tracked was selected by specifying the colour as in previous cases. Figure 3.6 shows the program window of this exercise and Fig.3.7 shows the data being tracked for further analysis.

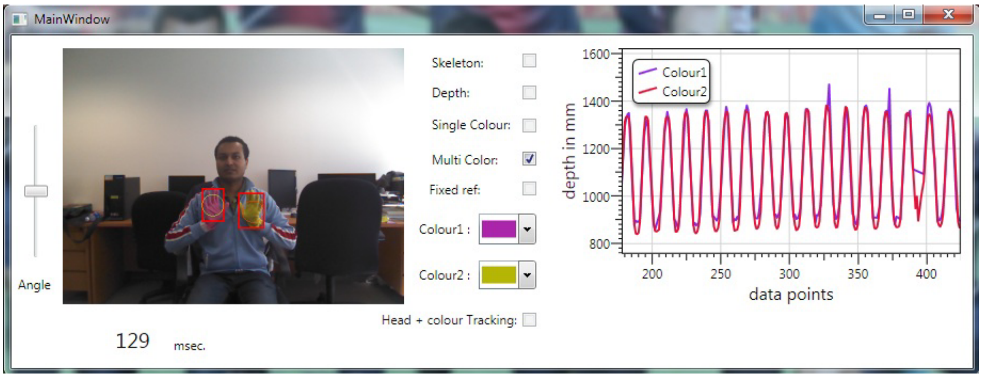


Figure 3.8: Tracking of multiple objects based on colour

3.3.4 Tracking of Multiple Mobile Objects Based on Colour

In the previous cases, there was only one mobile object and the other was in a fixed position. In this case, the program was designed to track two mobile objects by choosing the object colour to be tracked. The program identified the objects with the specified colours and drew a rectangle around each of them, and Kinect fed back the depth information of those detected objects.

In Fig.3.8, the subject was doing an arm-stretching exercise wearing two gloves of different colours (pink and yellow). The subject was asked to carry out the exercise while facing Kinect during which both arms were moved towards and away from the body. Kinect captured the objects' depth data and plotted it in the graph on the right. Analysing the enlarged graph in Fig.3.9 helped the physician to see if both the arms were being stretched equally and whether they were synchronised during the exercise. As mentioned in the case, one can see how many cycles of stretching is performed in a fixed time window and whether the patient was improving as the Telerehabilitation session progressed.

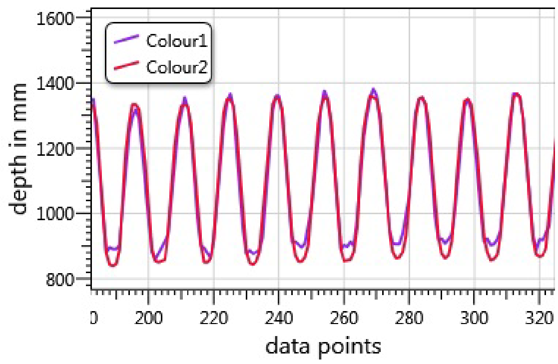


Figure 3.9: Enlarged image of the data plot

3.3.5 Detecting and Tracking of Multiple Body Joints

In some exercises, human skeleton based assessment can be very useful to the physician, such as during cane height assessment, balancing tests such as double leg stance and single leg stance [102] or even finger-to-nose task performance tests [103]. The user can select the joints to be tracked and plot the corresponding depth information on a graph.

In the first case here, the subject was asked to walk with the cane while the physician assessed the walking posture as well as determined whether the cane height was ideal for the patient. Since the whole body had to be visible to Kinect, 'Default' mode was used instead of 'Seated' for the skeletal stream. The depth range was set to 'Default' as well which enabled Kinect to track the body joints to the maximum distance away from the sensor. Figure 3.10 shows the positioning of the Kinect with reference to the subject and the joints being tracked. Kinect was facing the subject holding the cane, and head and hip were chosen to be tracked in this particular case.

Figure 3.11 shows the program window with the subject holding the cane and the selected joint positions detected by Kinect and identified by the red ellipses. The depth data was drawn as a line graph on the right. While analysing the

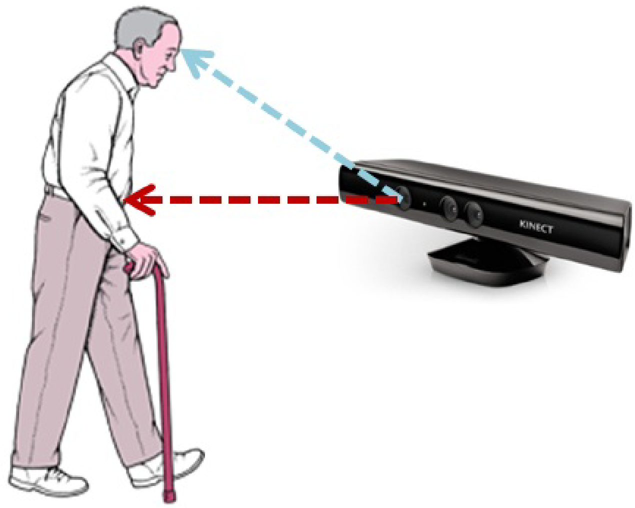


Figure 3.10: Kinect's positioning for cane height assessment

enlarged graph data in Fig.3.12, one can clearly see whether the subject stands straight or is leaning forward while holding the cane. Close positioning of the lines implies that both head and hip are on the same plane and the subject is standing straight. As the subject leans forward and walks, it can be seen that the hip position moved away from the head plane and thus the subject's posture is not upright. A similar method can be used for balancing tests to measure the subject's body movements while balancing on one leg.

With a normal 2D video, it is not easy for the physician to make such assessments unless the patient is asked to walk from a lateral point of view with respect to the camera. The problem in this situation is that the alignment of the patient's other body parts such as shoulder positioning is not clearly seen. Thus, depth tracking of certain joints helps in this scenario. Another assessment that can be efficiently done using this method is the finger-to-nose test. In this test, the subject's head and right or left hand was chosen to be tracked while carrying out the exercise as shown in Fig.3.13. Analysing the plotted graph helps to identify the number of exercise cycles carried out by the patient as well as

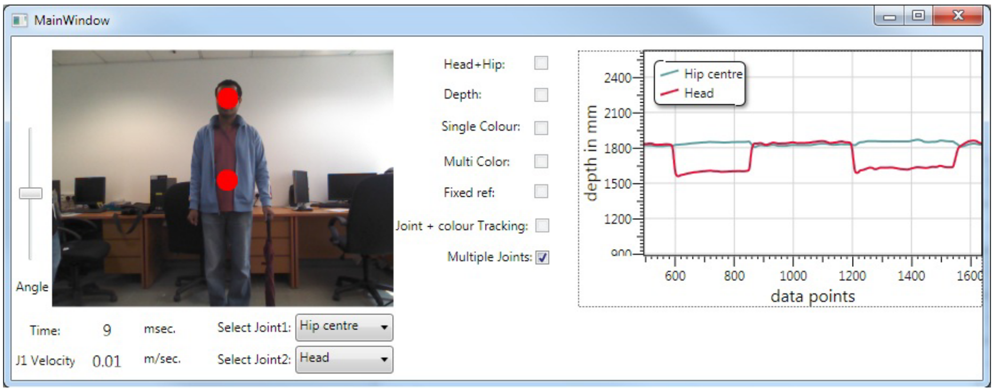


Figure 3.11: Tracking of body joints in cane height assessment

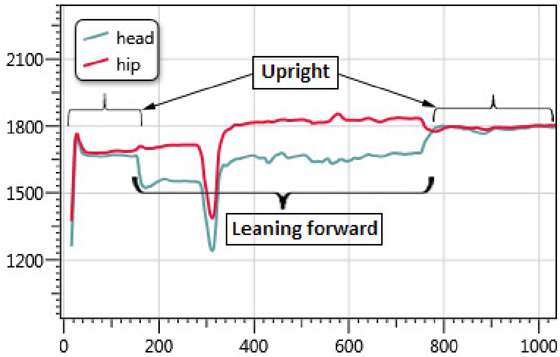


Figure 3.12: Analysis of the tracked data

whether the exercise was carried out properly (e.g. whether the hand touched the nose).

Skeleton tracking can also be used for the exercise discussed in Section 3.3.1 (i.e. assessing the case of walking in a straight line) only if the whole body is visible to Kinect. It can be modified to track only the hip position or any other joint position as desired by the physician. As explained in Section 3.2.4, the absolute velocity of Joint1 during the walk was calculated and displayed on screen (Figure 3.11 and Fig.3.13).

3.3.6 Velocity and Angle Tracking of a Joint during Exercise

In this experiment, the velocity measurement algorithm presented in Section 3.2.4 was used to measure the velocity of Joint1 and the angle between the

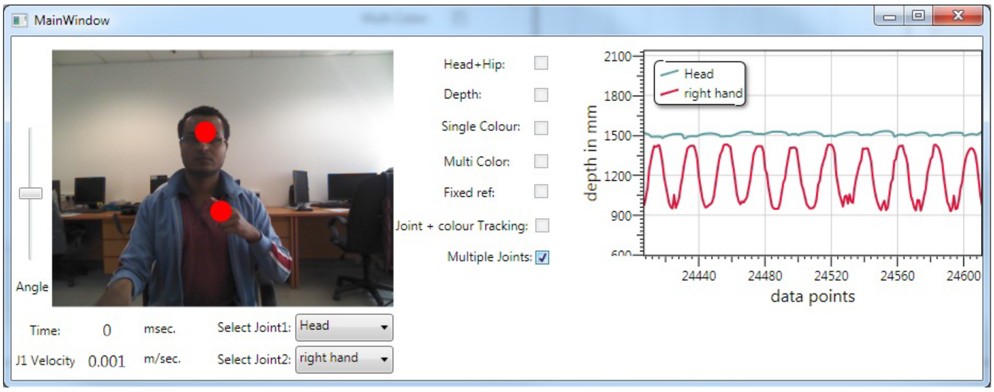


Figure 3.13: Finger-to-nose assessment using multiple body joints tracking method

shoulder, elbow and wrist joints was calculated as explained in Section 3.2.5. The exercise was performed over four segments as shown in Fig.3.14. The subject started from position 1 and stretched the arm to position 2 (180 degrees or 3.14 radians) in segment 1. In segment 2, the arm goes back to 90 degrees (1.55 radians) as in position 3. Segment 3 is folding the arm fully so that angle goes closer to zero as shown in position 4. Finally, in segment 4, the arm goes back to position 3.

This movement cycle is repeated and the velocity of the moving hand as well as the angle formed by the hand was captured in real time and plotted on the graph as shown in Fig.3.15. The four segments are marked in the graph and the unit used for angle was radians and that for absolute velocity was m/s. The plot shown is for the case when the motion is uniform throughout the exercise which may be an indication of a normal movement. The velocity can be seen changing cyclically from zero to a maximum value during smooth arm movement.

Figure 3.16 shows the graph plot of an exercise cycle carried out by another patient. While analysing the plotted data, one can see that the stretching part of the motion (segments 1 & 2) was carried out slower than folding part of

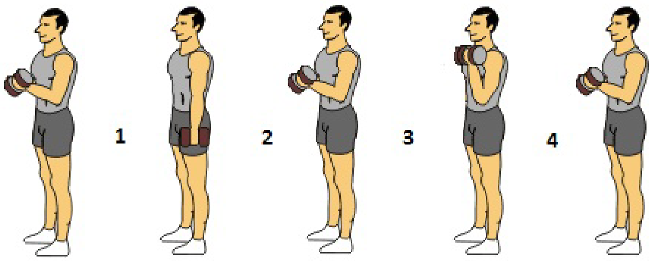


Figure 3.14: Exercise cycle [5]

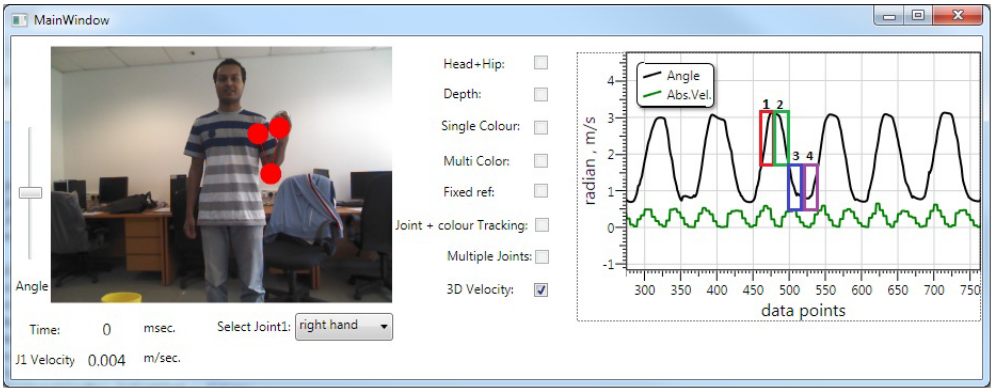


Figure 3.15: Velocity and angle tracking with the four segments highlighted

the motion (segments 3 & 4). Correspondingly, the absolute velocity plot also showed the same pattern. Velocity spikes are seen in the folding segments, which indicate a quicker motion, whereas lower values were measured at other times. This indicates that the patient has some trouble stretching the arm with ease and this pattern may not be clearly visible with a usual 2D video. Thus, this method may be useful for physician's assessment.

3.3.7 Delay Incurred by Depth Tracking

Although these measurements are useful and enhance Telerehabilitation assessments, they incur processing delay while extracting the depth data. More specifically, the majority of the delay occurs from processing the colour tracking algorithm. Although the colour filter being used in this framework is the fastest

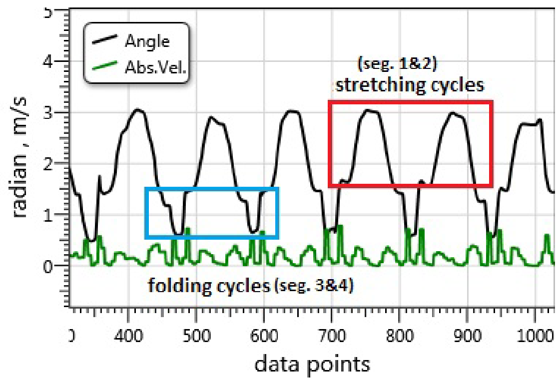


Figure 3.16: Simulated image of plotted data for analysis

Table 3.1: Delay encountered in all the scenarios in Section 3.3

Scenario	**Average Delay** (milliseconds)
Tracking single mobile object	60
Tracking single mobile object with respect to a fixed object	70
Tracking of single mobile object with reference to a moving body part	75
Tracking multiple mobile objects based on colour	130
Detecting and tracking multiple joints	5

of all currently available, it is not immune to delay. Table 3.1 shows the average measured delay in all the five cases discussed in Section 3.3. It can be seen that using skeletal tracking induces almost no delay while processing of the colour tracking algorithm accounts for the majority of the delay.

Kinect's skeleton stream works in parallel with the colour image stream and they both operate at the same frame rate. Both streams are fired at the same instance as well and this is the reason for having almost no delay when tracking is based on skeleton joints. In the case of tracking based on colour, the program takes the colour frame first and then performs the colour detection algorithm. These two processes cannot be done in parallel and this is the cause for the delay in all other cases in Table 3.1. However, this delay is still negligible in a regular video conferencing session. In the colour tracking scenario, each colour frame has to undergo the tracking algorithm individually and the tracked object's position is attached together with the frame in the form of a rectangle or ellipse before sending them to the receiver as discussed in Section 3.3. Since each frame is sent to the receiver side individually using a common 'Timer' function, it is automatically synchronised with the depth data and thus, there are no issues with depth data arriving out of sync with the video data.

3.4 Summary

A framework for extracting the depth information in a Telerehabilitation video and transmitting together with 2D images was presented in this chapter. Different methods of tracking specific objects based on colour and human skeleton using Microsoft Kinect were discussed in detail. Multiple scenarios of Telerehabilitation exercises leveraging on the framework were explored. Collected depth data were analysed for the assessment of exercises carried out by the patient and further possibilities of utilising this data were discussed. This framework can be a very useful tool to get a good sense of spatial resolution in situations when conventional 3D video transmission can be extremely challenging due to the limited network bandwidth.

There are certain limitations in the current framework and the effectiveness of the overall system can be further improved. In the current framework, the data analysis has to be done manually by the physician and this can be tedious if done over a long period of time. Improvements can be made to this platform by having the software automatically analyse the extracted data and provide quantitative measures on the effectiveness of the exercise being carried out (e.g.

by measuring the stretch distance as well as the number of arm stretches in the exercise discussed in Section 3.3, or measuring the number of cycles carried out in the finger-to-nose task performance assessment). Development of such algorithms to analyse the extracted joint data and implementation of the developed algorithm to automate the performance analysis of the patient will be presented in Chapter 5 in detail.

While many studies show the acceptability of Telerehabilitation, as mentioned in the introduction chapter, flexible solutions that are usable under low bandwidth network environments are rare. Chapter 4 presents the design of designated consultation categories with pre-set parameters that are tailor-made for different types of rehabilitation assessments so that the user can carry out the Telerehabilitation assessments without having to worry about the optimal video quality settings. The chapter also introduces an improved bandwidth adaptation algorithm. The test results on the system performance in different consultation categories under fluctuating bandwidth conditions is presented to verify the efficiency of the developed platform.

Chapter 4

Design of Designated Consultation Classes for a Telerehabilitation Application

4.1 Introduction

Telerehabilitation (TR) is an important sub-discipline of Telemedicine in which modern telecommunication and information technology are used to deliver rehabilitation services over a distance. This is achieved by the use of technologies including audio, video as well as virtual reality transmitted over the Internet. A comparison with traditional, in-person rehabilitation services reveals that the cost can be reduced while maintaining or even improving overall effectiveness with appropriate use of Telerehabilitation [104]. The study conducted by Schein et al. notes that TR is especially helpful for people in bringing advantage in terms of (1) decreased travel between the rural communities and specialised urban health centres, (2) availability of specialised clinical support in local communities, (3) indirect educational benefits for remote clinicians who participate in teleconsultations, and (4) alleviation of feeling of isolation for rural clinicians when the session involves rural clinicians and their specialist counterparts from the cities [105].

According to the 2013 report from International Telecommunication Union (ITU), 41% of the world's households are connected to the Internet and 50% of them are in the developing countries [17], as mentioned in Chapter 1. However, the report notes that high-speed access to the Internet is still limited in developing countries due to the cost factor with a fixed-broadband service accounting for 30.1% of average monthly incomes. Due to this reason, in majority of the developing nations, the Internet speed can be in the range of 256 kbps or less [106]. This means that, for a TR system to work satisfactorily in such environments, it should be able to adapt its content quality according to the available Internet speed. Even in developed countries, high and fixed bandwidth comes at a premium and it is often the group of people for whom Telerehabilitation would be most useful who are least likely to have premium Internet access. For example, as mentioned in Chapter 1, the recent statistics from the Infocomm Development Authority (IDA) of Singapore reports that a decent speed Internet connection (more than 50 Mbps) costs on average $50 or more a month. The presented data also reveal that for Internet networks with maximum speed of 50 Mbps or below, the uploading speed is in terms of a few hundred kbps, which is well below the necessary requirement for a high data rate communication [2][3].

A typical TR scenario includes motion assessments related to gait, fine motor skills and gross motor skills of a patient. Fine motor skills refer to activities related to fingers, wrists, and eye-hand coordination, all of which involve smaller muscle movements [107]. Gross motor skills refer to activities such as the process of sitting, walking, running, and jumping during which the major body muscles are in motion [108]. The speed at which these various exercises are carried out varies from each other; fine motor exercises involve fast movements whereas gross motor exercises are slower. Thus, the video quality requirements for each of these situations will be different. Some need a high resolution, whereas some others need a high frame rate. By optimising the video parameters such as frame rate and resolution, assessment performance in each of these cases can be maximised in a limited bandwidth environment.

A study conducted by Hoenig et al. [64] examined the effect of differing network environments on measurement accuracy when examining physical functions using a standard, off-the-shelf videoconferencing technology for Telemedicine. The study provided promising results for assessing fine motor function when the bandwidth was high (768kbps), but the accuracy dropped significantly when the same system operated at lower bandwidths including 384kbps and 64 kbps. Moreover, accuracy was suboptimal at all bandwidths for assessing gross motor functions (e.g., gait) and it only rose to acceptable levels relative to in-person assessment with use of slow-motion review of a high quality video-recording. The authors suggested that differing types of motor function have differing technological needs (e.g., frame rate, resolution, stereoscopic image) for optimal assessment via Telehealth. The study concluded that improved technology and infrastructure were needed to better meet the Physical therapist/Occupational therapist's

(PT/OT) clinical requirement for Telehealth.

With the insights gained from the above study, in this chapter, the author introduces the concept of having different categories for tele-video transmission in a TR session, termed TR Consultation Categories, particularly for PT/OT TR consultations, where users can select a particular category with a pre-defined parameter setting which ensures maximum transmission of clinically useful data in limited bandwidth environments. The techniques used in this chapter are based on Chapter 2, which discussed development of a basic Telemedicine framework as well as different methods to reduce the data size while conducting a consultation session over a narrow bandwidth network, and Chapter 3, which discussed different kinds of spatial data extraction methods using Kinect sensor. A new improved approach is also formulated for the bandwidth adaptation as explained in Section 4.3. This chapter further discusses the effectiveness of having appropriate TR Consultation Categories for different TR sessions followed by the necessary evaluation to validate the claims.

4.2 Literature Review

The acceptability of telecommunication technology use in rehabilitation practice has been substantiated in many studies. Finkelstein et al. conducted a pilot study on home-based physical Telerehabilitation and the results were promising with an acceptance rate of over 80% from the patients [67]. An early study by Dick et al. reported that 76% of the patients who participated in the Telemedicine assessment were satisfied with the system [68]. Regarding the technical acceptability of information obtained via Telerehabilitation, an overall agreement of 92% was reached between the video based assessment and the face-to-face assessment in a study conducted by Rintala et al. [109]. Sanford compared an individualised, comprehensive multi-factorial intervention aimed at improving a patient's mobility provided by a therapist either in-person in the patient's home or through use of TR and found that the two methods identified similar numbers of problems, recommended similar number of interventions, and the interventions were adopted at similar rates with either mode of service delivery [69].

On a similar note, a study conducted by Schein et al. on the inter-rater reliability between in-person and TR assessment of Functioning Everyday with a Wheelchair-Capacity (FEW-C) demonstrated excellent results with an interclass correlation coefficient of 0.91, although the system was tested under high bandwidth conditions [110]. In another separate study, Schein et al. compared TR sessions on wheeled mobility and seating assessments, with in-person assessment scenarios and the results indicated that the TR sessions were equally effective as the gold standard in-person assessments [110].

Sanford et al. conducted clinical trials in a study to evaluate the effectiveness of PT/OT sessions through tele-video technology for follow-up visits. The study reported that potential use of tele-video sessions is encouraging to meet the needs for in-home PT/OT [111]. Another study on conducting a remote assessment of low back pain by Truter et al. also addressed the practicality of the TR, by physical therapists in rural clinical settings in particular. The participant satisfaction was good overall; with acceptable performance in assessments and strong correlation with in-person results and with high reliability scores [112].

These emerging evidences are encouraging for the use of TR as a supplement to or even in place of face-to-face sessions.

Although there are existing systems for Telemedicine purposes, they are not particularly designed to perform well in low bandwidth environments. A versatile system for Telerehabilitation was developed by Parmanto et al. [70], that was used in some of the above mentioned studies, which supported audio visual data exchange. However, the system was designed for broadband networks and thus it is not suitable when the bandwidth drops to low levels. Panayides et al. [71] developed an open source Telemedicine platform for wireless medical video communication. Similarly, this solution did not specifically address the issue of communication in low bandwidth networks as well.

From the literature survey conducted, no prior work was found on the development of solutions which are adaptable to the stringent requirements of low bandwidth networks in terms of multiple data parameters and at the same time, tailor-made to fit a Telemedicine application with the necessary medical knowledge rather than information from a pure engineering background. This chapter presents the design and development of a Telerehabilitation system, for PT/OT use in particular, in which the user is able to select the consultation category based on the assessment to be performed. Each consultation category is designed to give priority to different video parameters (e.g. frame rate, compression quality, colour etc.), depending on the application requirements as mentioned earlier. Evaluations are done while the system was operated in a limited bandwidth environment and conclusions are drawn on the effectiveness of such a system.

4.3 System Overview

4.3.1 System Architecture

The system is simple at the PT/OT's end with a normal webcam and microphone, and the software running on Windows 7 PC. At the patient's end, the webcam is replaced with Microsoft's Kinect sensor in order to make use of some of its extra functions such as depth sensing as explained in Chapter 3. The overall system runs as a client-server architecture whereby a central server is the connection point for both clients; the patient and the PT/OT. As mentioned in earlier chapters, audio, video and other data from either client side are transferred through dedicated ports at the fixed server at all times.

4.3.2 Novel Bandwidth Adaptation Method

The bandwidth detection algorithm presented in Chapter 2 was based on sending a fixed size packet from the sender and calculating the available bandwidth based on the time difference between the sending time and the acknowledgment return time from the receiver. This method, however, was not ideal for detecting the speed in low bandwidth networks due to the additional payload caused by the fixed size packet. The fundamental assumption was that, processing and other related delays are negligible compared to the actual return time of the message packet. This assumption holds true only if the packet size is large, in terms of hundreds of kilobytes, otherwise the detected bandwidth value will be inconsistent. The algorithm mentioned in Chapter 2 employed a message packet sized 200 kilobytes sent in every two minutes and this induced additional burden on the already limited network bandwidth. Another limitation of this algorithm was that it was not quick enough to identify the changes in bandwidth and adapt the video quality accordingly.

To improve on the aforementioned limitations, a new method is introduced in this chapter to accurately detect the available bandwidth and the algorithm flowchart is shown in Fig. 4.1. A timer is set-up to trigger every 5 seconds to measure the data rate, for the next two seconds from the trigger, at the sending client (SBW1) as well as the data rate at the receiving client (RBW1). If SBW1 found to be equal to RBW1, this implies further availability of bandwidth and thus the video parameter is increased at the sending side in order to maximise the bandwidth utilisation. If the selected consultation category is of frame rate priority, compression quality (CQ) will be increased by factors of 5 till a maximum value of 80% is reached. Once the CQ value hits 80% and there is still bandwidth available, the frame rate will start to increase up to the maximum value of 30 is reached. Similarly for the resolution priority category, frame-rate will be increased by 1 till the maximum value of 30 frames per second (fps) is reached. Once the maximum frame rate is reached and bandwidth is still available, CQ will be increased till a maximum value of 80%. This is done to ensure the system is able to utilise the available bandwidth to the maximum extent possible.

If SBW1 is more than RBW1, which implies that the maximum available bandwidth is reached at the receiver end, the corresponding parameters will be reduced according to the selected consultation category until the minimum value is reached. The minimum value for CQ is set at 10 for frame rate priority classes, whereas the minimum frame rate is set at 6 for resolution priority classes. These values are chosen as minimum requirement empirically based on numerous trial runs as they were found to be the minimum values for ensuring a meaningful consultation session. The parameter increment/ decrement, as shown in Figure 4.1, were chosen roughly based on additive-increase/multiplicative-decrease (AIMD) algorithm [113]. The whole process repeats every 5 seconds and thus, the bandwidth adaptation is much faster than the earlier method discussed in Chapter 2. This interval, i.e. 5 seconds, is an empirical choice to strike a balance between adaptation speed and program resources. If too long a sampling value is chosen for this purpose, the adaptation will be slow as a result; similarly, too short a value will cause the program to be continuously measuring the data rate, which is also not desirable to the system.

4.3.3 TR Consultation Categories

As mentioned earlier, different consultation categories were provided to the user to choose from, depending on the assessment requirements. Leveraging on the techniques mentioned in Chapter 2 and Chapter 3, five categories were identified for classification. The parameters varying in each category are (1) frame rate, (2) resolution or compression quality, (3) colour, (4) manual or automatic cropping and (5) spatial data extraction using Kinect sensor. Although the default values are set for each parameter in each category, the users have the freedom to change some of them according to requirements. Details of the five consultation categories and their default parameter settings are explained as follows:

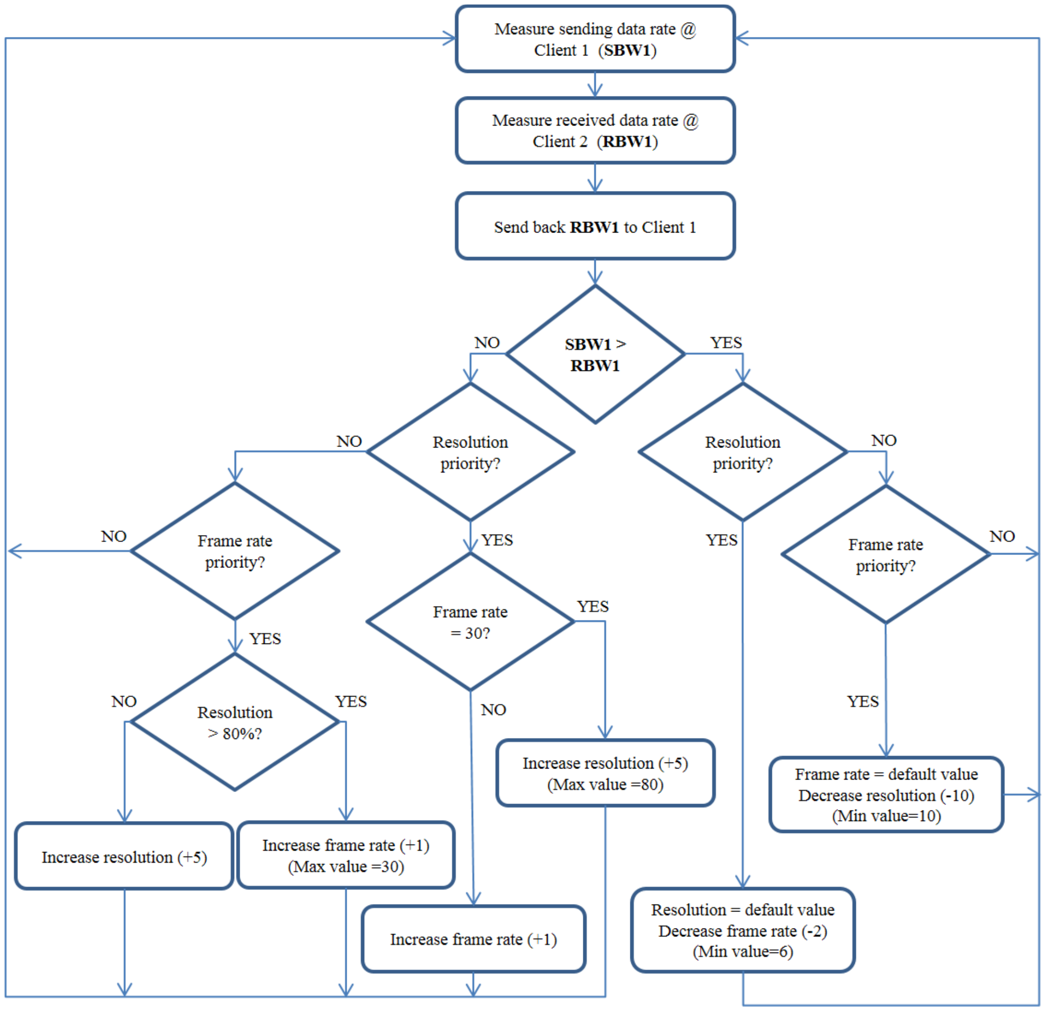


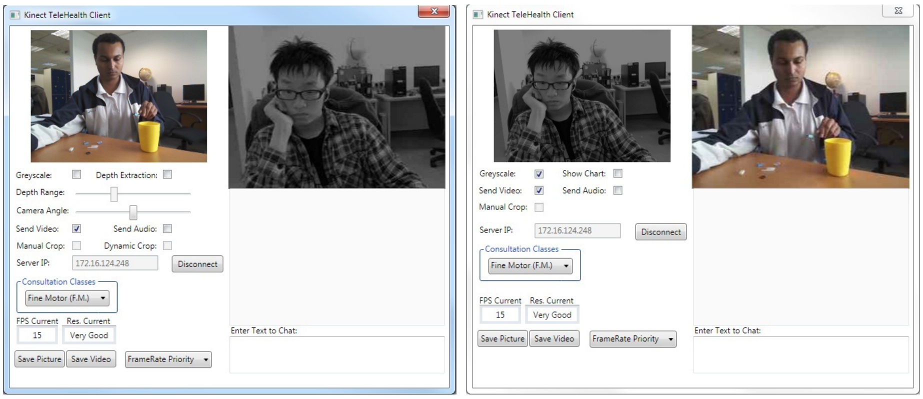
Figure 4.1: Bandwidth detection algorithm at client 1

4.3.3.1 Fine Motor

Fine motor in a human body refers to the smaller muscles (e.g. hands, wrists, fingers, etc.). Activities relating to fine motor skills include picking and sorting of small objects using tongs or tweezers, holding and using feeding utensils, etc. In order to make an accurate assessment during a typical rehabilitation session, the PT/OT might need to focus on the quality of the movement to identify problems with incoordination or trembling. . If this is the requirement, in a low bandwidth Telerehabilitation session, priority would be needed to be focused on frame rate so that all of the fine motor movements are able to be seen. Other parameters such as video colour and resolution may not be as critical in this particular situation and thus given less weightage in consideration.

At other times, it may be important to be able to detect problems related to the interface of the hand with the environmental task parameters (e.g., fumbling with buttons, problems manipulating a tool or a utensil properly), in which case a highly detailed view may be important and parameters such as video resolution and/or colour would need to be prioritised in a low bandwidth session. Moreover, it may be necessary to repeat tasks so that they can be viewed with a high frame rate to assess the quality of the movement and again with high resolution or video colour to assess the function of the hand and fingers in particular aspects of the task being performed. To cater for such circumstances, the system is designed to allow the user to switch the priority from frame rate to resolution by manual intervention, with the default system setting being frame rate priority scheme.

Spatial data extraction, as mentioned in Chapter 3, is optional in this category with the user having the ability to activate it when needed. Figure 4.2 shows a sample screenshot of the application at the patient's side when the Fine Motor (F.M.) category is chosen with colour information from the patient's end activated. The frame rate is set at minimum 15 fps by default while resolution is varied dynamically up to 80% if the bandwidth permits, with a minimum guaranteed CQ value of 10%. Once the maximum value of CQ is reached and the system detects further available bandwidth, the frame rate will be increased in order to make full use of the network. Cropping is not activated in this case since the relative position of body parts with respect to the background may be useful for certain assessment purposes.



(a) patient's end (b) health professional's end

Figure 4.2: Sample screens with Fine Motor category selected

4.3.3.2 Gross Motor

Gross motor skills refer to the movement of major muscles of the human body during exercises such as walking, weight lifting, throwing a ball, etc. Compared to fine motor exercises, gross motor movements are slower in pace, but assessing continuity of movement nonetheless may require a high frame rate (e.g., concern about intermittent loss of balance while walking, determining the presence of abnormalities in gait cadence). However, sometimes the clinical concern arises about subtle movement abnormalities (e.g., normal vs abnormal amount of sway, step width), in which case relative priority may be needed for resolution over frame rate. Thus, as with fine motor movements, it is important the clinician be able to utilise the optimal technological parameters and to be able to alter the parameters during the clinical visit as the evaluation progresses.

The resolution priority case will be activated by default in this category by setting the minimum compression quality (CQ) of 30% to be maintained at all times, thus ensuring a minimum image resolution, while dynamically changing the frame rate in accordance with the available network bandwidth in every five seconds. Based on empirical data, the minimum value for frame rate is chosen as 6 while the maximum value was set at the camera limit of 30. Once the maximum frame rate value is reached and available bandwidth is still more than the data rate, CQ value will increase in order to increase the consultation quality by maximizing the bandwidth utilization. However, to cater for the other scenarios which require the high frame rate as mentioned above, the user will have an option to switch the priority from resolution to frame rate while in this category as well.

Finally, some gross and fine motor tasks require ability to discern movement in three dimensions and/or discern the interface of the patient with the environment. Examples of the former might be stepping continuity assessment while turning or evaluating patient performance during contextually embedded dynamic tasks such as climbing stairs, transferring to the toilet or a wheelchair, reaching and manipulating items during food preparation. Examples of the latter include assessing foot clearance while walking, fumbling while manipulating objects. Since the background information may be needed to monitor the relative position of body parts and/or problems interfacing with the environment, cropping is deactivated by default in this category. As in the previous case, spatial data extraction and colour are set as optional parameters. Figure 4.3 shows a screenshot of the application when Gross Motor (G.M.) category is selected with the spatial data extraction feature activated. The image is shown to be tracking the arm movement while the patient carries out a weight lifting exercise. The angle formed between the joints of the shoulder, elbow and hand is measured and displayed together with the hand velocity data by using the spatial data

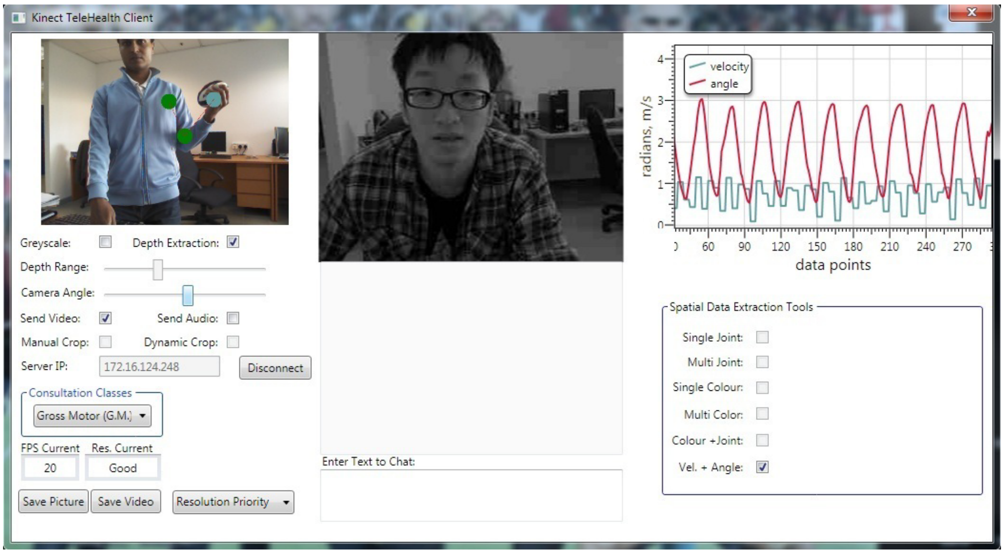


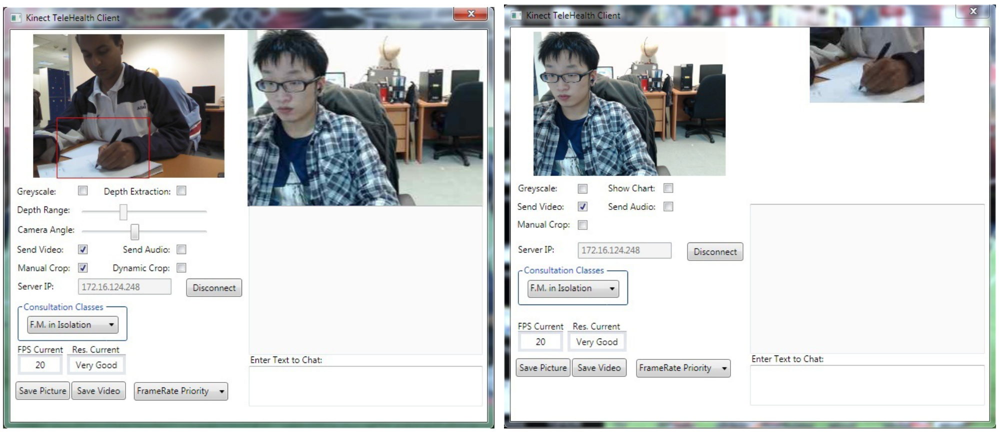
Figure 4.3: Sample screen with Gross Motor category selected and spatial data activated

extraction feature.

4.3.3.3 Fine Motor (F.M.) in Isolation

This category is a variant of F.M. category discussed earlier, but catered to different fine motor exercises. Other examples of fine motor exercises include finger tapping, handwriting, etc. While carrying out such exercises and monitoring through video, only a part of the screen is the area of interest to the physician. Thus, in such cases, the unwanted areas of the screen can be omitted from being sent over the network by employing the cropping feature. In order to select the region of interest, the user just has to draw a rectangle across the desired part of the image screen. This feature helps to reduce the data payload further and thus ensures a smoother Telerehabilitation session even in limited network bandwidth environments.

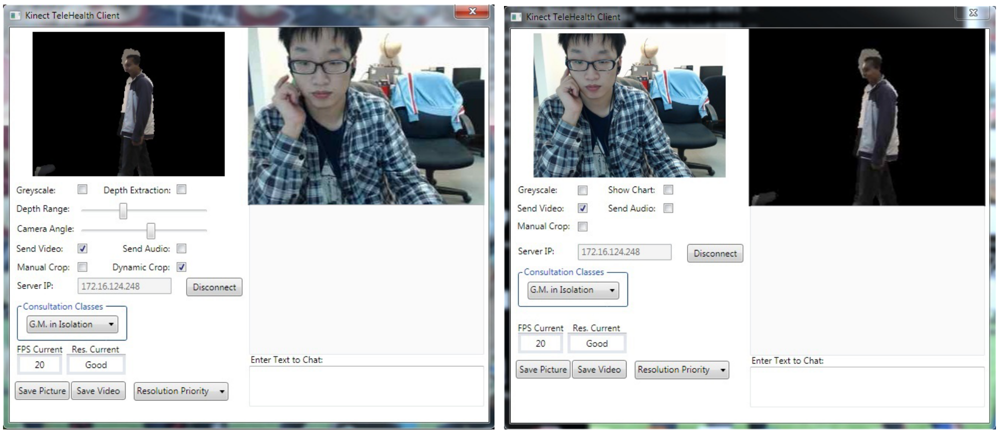
This category is similar to Section 4.3.3.1 except that the tasks can be performed in isolation by the cropping mechanism. The user will also have the



(a) patient's end (b) health professional's end

Figure 4.4: Sample screens with F.M. in Isolation category selected and manual copping enabled

option to turn on colour, if needed, since cropping mechanism helps to make room for more data to be accommodated. Other than manually cropping off the area of interest in the screen, the user can activate dynamic cropping as well, provided a Kinect camera is used instead of a normal webcam. It works by masking out the objects further than a specified distance from the camera with the help of Kinect's depth sensor. This function is enabled only if Kinect is detected by the system. Since the data size can be significantly reduced by the cropping mechanism, the minimum frame rate value to maintain in this category was chosen as 20, while the resolution remained dynamic in accordance with the available bandwidth of the network with the same range of values as mentioned in Section 4.3.3.1. Spatial data extraction and colour are again optional depending on the user's preference. Figure 4.4 shows a screenshot of the application in this category with manual cropping activated. As in the earlier case, the user will have an option to switch priority from frame rate to resolution in this category as well.



(a) patient's end (b) health professional's end

Figure 4.5: Sample screens with G.M. in Isolation category selected and dynamic copping enabled

4.3.3.4 Gross Motor (G.M.) in Isolation

This category is a variant of Section 4.3.3.2 in which gross motor tasks are assessed, but catered to different exercises. This is based on resolution priority case as well, with frame rates varying according to the available network speed every 5 seconds. The CQ value to maintain in this category was chosen to be at a higher rate of 40% due to the data size reduction made possible by the use of cropping feature, with the same range of frame rate values as in Section 4.3.3.2. Hence, this category is useful for situations where only the patient's body is the area of interest and the surrounding environment can be ignored. The resulting data reduction allows the video to be transmitted with colour data. Similar to previous categories, spatial data extraction feature is optional and can be activated when needed. Again, the priority scheme can be switched from resolution to frame rate upon user intervention. Figure 4.5 shows a screenshot of this category with dynamic cropping turned on while assessing a walking exercise performed by a patient.

4.3.3.5 Manual Category

Although there are four categories with preset parameters to choose from, some assessment may require different parameter settings; e.g., the different frame rate or resolution values. To cater to such cases, a manual category is constructed in which the user can adjust the frame rate or the resolution quality freely. Although the system does not alter either the frame rate or resolution dynamically in this category, the bandwidth detection algorithm is still running and recommended values for both parameters are shown to the user. However, the selection of these parameter values is open to the user's discretion and consequently, the system would not guarantee a smooth performance if higher than recommended values are chosen in a limited network bandwidth environment.

All the parameters available in the system are made optional in this category with the user having the freedom to activate them when the need arises. Figure 4.6 shows the system with manual category selected.

Table 4.1 summarises the default settings of all parameters in each of the five consultation categories explained above. The parameters in the first four categories are programmatically set and only the manual category allows the user to change the values of frame rate and resolution from a pre-set list. As mentioned earlier, parameters such as colour, cropping, and spatial data extraction can be activated if the need arises during the consultation session and thus have been set as optional.

Table 4.1: Overview of consultation categories in the Telerehabilitation system

Category	**Frame-Rate** (fps)	**Resolution** (CQ)	**Colour**	**Cropping**	**Spatial Data Extraction**
Fine Motor	15 (minimum)	Varying (10%-80%)	Optional	Off	Optional
Gross Motor	Varying (6-30 fps)	30% (minimum)	Optional	Off	Optional
F.M. in isolation	20 (minimum)	Varying (10%-80%)	Optional	Optional	Optional
G.M. in isolation	Varying (6-30 fps)	40% (minimum)	Optional	Optional	Optional
Manual	User defined	User defined	Optional	Optional	Optional

4.4 System Evaluation

4.4.1 Minimum Bandwidth Requirements

Experiments were conducted in order to determine the bare minimum requirement for the system to function satisfactorily in frame rate priority and resolution priority cases. The Manual consultation category was chosen to run the experiment, and frame rate and compression quality values were manually changed while colour information as well as spatial data extraction features were disabled. The experiments were conducted in two sets; first set using Kinect camera/webcam with 640x480 frame resolution (at the patient's end) and the second set with a built-in laptop webcam with 320x240 frame resolution (at the PT/OT specialist end). Although the difference in frame resolution was exactly half in the built-in webcam case as compared to the Kinect camera, the bandwidth utilisation did not follow this scale exactly, probably because of compression algorithm dynamics.

Table 4.2 shows the measured bandwidth while the system was in operation

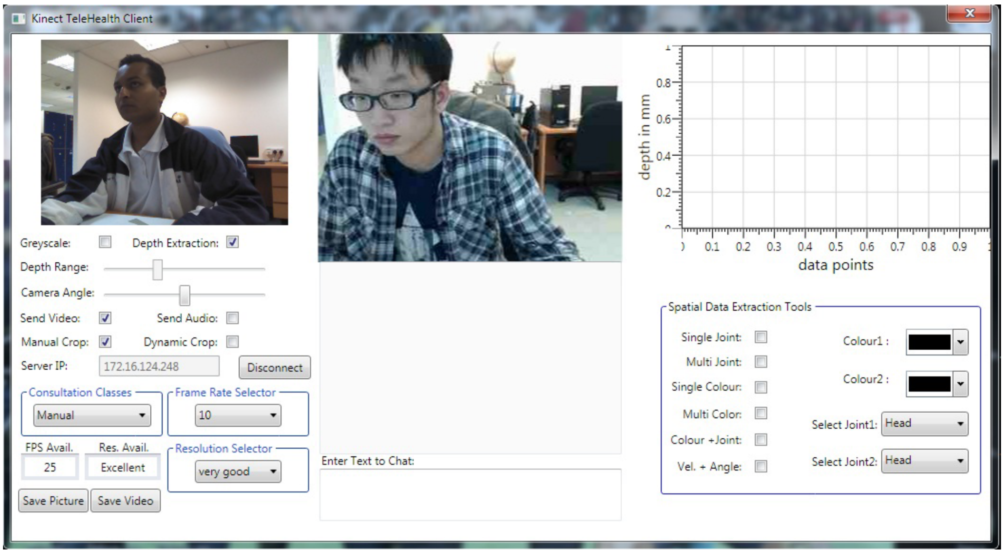


Figure 4.6: Sample screen with Manual category selected

under the aforementioned conditions. From the data, it is clear that the system would function smoothly even when the available bandwidth drops below 128 kbps, if operated with its minimum parameter settings. While using the system with a built-in webcam in a laptop, it can function in resolution priority categories even when the bandwidth availability drops below 50 kbps. This is one of the most important features of this system which enables the teleconsultation session to be carried out in bandwidth scarce environments.

4.4.2 Efficiency of Bandwidth Adaptation Algorithm

The ability of the system to adapt itself to the dynamics of available network bandwidth is key to the effectiveness of its implementation in bandwidth scarce environments such as rural areas. This test was performed to measure the effectiveness of this system's adaptability while the available bandwidth fluctuated. A third party software, Netlimiter [114], was used for simulating such a scenario. The bandwidth was set at an initial value of 32 kBps (256 kbps) and slowly increased to 44 kBps (352 kbps) in short steps of 4 kBps, and then reduced down

Table 4.2: Bandwidth measured when the system operated with minimum parameter settings

Camera	**Priority**	**Frame-Rate** (fps)	**Resolution** (CQ)	**Colour**	**Spatial Data Extraction**	**Bandwidth used (kbps)**
Kinect/ Webcam	Frame-Rate	15	10%	Off	Off	100
Kinect/ Webcam	Resolution	6	30%	Off	Off	60
Built-in Webcam	Frame-Rate	15	10%	Off	Off	70
Built-in Webcam	Resolution	6	30%	Off	Off	40

to 28 kBps (224 kbps) in a similar fashion, while the data rate adaptation of the system was monitored. Figure 4.7 shows the chart with the data rate variation carried out by the software during this experiment, when the Telerehabilitation platform operated in the Fine Motor category. The figure displays the frame rate maintained (FPS) as well as the resolution value (CQ) while adapting the data rate to the available network bandwidth (BW). The horizontal axis shows the time in minutes, whereas the vertical axis shows the data rate in kBps. The data rate plot was extracted from the simulating software while the frame rate and resolution parameters were recorded from the TR platform using a display box.

Similarly, Fig.4.8 shows the bandwidth adaptation the TR system was operated in the Gross Motor category. The minimum resolution value (CQ) was maintained throughout the experiment while the frame rate (FPS) varied according to the available Bandwidth (BW), as shown in the figure. Both experiments were repeated three times to obtain an average value of parameter settings during the bandwidth adaptation.

As shown in Fig.4.7, since the F.M category utilises frame rate priority streaming by default, the frame rate is kept at a constant value of 15 fps by the system. As the available BW was increased from 32 kBps up to 44 kBps, the corresponding increase in the effective data rate is clearly visible from the graph. This is achieved by the adaptation algorithm in the TR platform that steadily increased the CQ value, thereby rendering a better quality video to the receiver. Again, as the available BW was gradually lowered to 28 kBps, the CQ value was correspondingly lowered by the system to ensure the continuity of the session.

Similarly, it is clear from Fig.4.8, which shows the TR system being operated in the resolution priority streaming, that the system is adapting its data rate to the available bandwidth by varying the frame rate while maintaining a minimum CQ value and it is able to quickly respond to the dynamics of the network traffic. This implies that the improved data rate adaptation algorithm is able to adapt the parameter effectively and make efficient use of the available network bandwidth.

4.4.3 Efficiency of Available Bandwidth Utilisation

This test was conducted to quantify the ability of the system to successfully measure and utilise the maximum available bandwidth, and thereby ensure a good quality video consultation session at all times. Again, Netlimiter was used to simulate different bandwidth environments by restricting the data transfer rate at the server and the utilisation was measured in each environment. Ta-

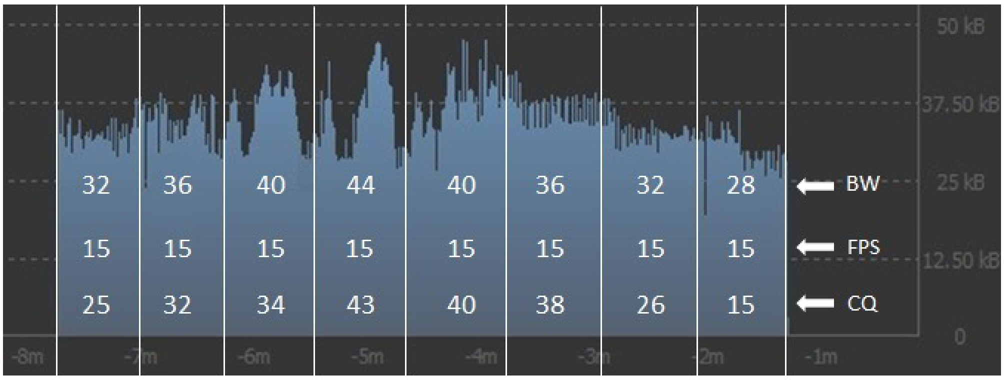


Figure 4.7: Efficiency of the bandwidth adaptation algorithm in Fine Motor category

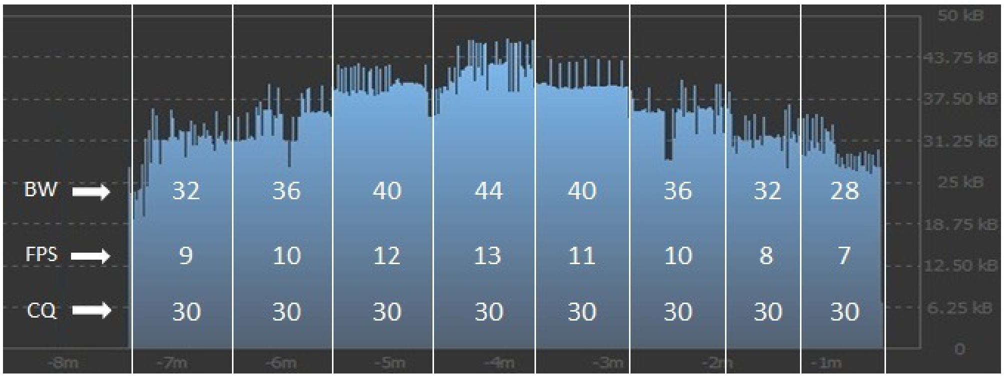


Figure 4.8: Efficiency of the bandwidth adaptation algorithm in Gross Motor category

ble 4.3 tabulates the percentage utilisation of the available bandwidth in four different bandwidth scenarios. Columns 2 to 4 show the system's bandwidth utilisation in F.M. and G.M. which employs the bandwidth adaptation algorithm, and the last two columns show the utilisation if the system is operated without any bandwidth adaptation. Manual category is selected in the latter case, since bandwidth adaptation was not functioning in this category, with the parameter values fixed at a default setting in order to suit the slowest bandwidth scenario (choosing higher parameter setting will cause system hang due to excessive data being transferred through a narrow network path).

Comparing the results in Table 4.3, in all the scenarios of F.M. and G.M., the

Table 4.3: Bandwidth utilisation by the system in different network environments

Available Bandwidth (kbps)	**Bandwidth Used by the System F.M.** (kbps)	**Bandwidth Used by the System G.M.** (kbps)	**Average Utilisation in F.M. and G.M. (%)**	**BW Utilisation with No Adaptation** (kbps)	**BW Utilisation with No Adaptation (%)**
128	124	125	97	125	97
256	251	239	96	124	48
384	376	378	98	130	34
512	503	474	95	125	24

average utilisation was found to be above 95% of the available bandwidth and hence ensuring that the system provided a good quality consultation session at all times; whereas in manual case, the bandwidth remained constant even when the available bandwidth increased, resulting in bandwidth underutilisation.

4.4.4 Video Quality Assessment Survey

A survey was conducted to gather information on the video quality delivered in low bandwidth networks while employing the data reduction and adaptive streaming techniques mentioned in this chapter. Two exercises were chosen, such that one involves fine motor motion and the other involves gross motor motion, to provide quantitative measures on the system performance. The subject who performed the exercise was a healthy individual and prior consent was obtained on recording the video. The first exercise was a finger-tap work out carried out by the subject. The subject was asked to perform the exercise by tapping the index finger on the table ten times at around two taps per second, repeated over three sets. The exercise video was streamed across a low bandwidth network of less than 200 kbps, first by using the F.M. in isolation category which employs the adaptive bandwidth algorithm and then by using the manual category where no bandwidth adaptation strategy was employed. Similarly, a second exercise was transmitted across a low bandwidth network as well, in which the subject was asked to perform elbow flexion-extension motion repeated again over three sets such that in each set, set five full extensions of the elbow were followed by a single half extension. The second exercise was again, initially run by selecting G.M. category followed by manual category.

The received video streams in all four cases were recorded and evaluated by 12 independent testers, including two physicians, two certified therapists as well as four care providers and four technical experts who were trained on the use of the system. The recorded videos were stored in a central storage space and the testers were asked to evaluate the downloaded video on a local computer. The recorded video files can be viewed at: $http://bit.ly/1t4NsUv$, $http://bit.ly/1vvg89T$, $http://bit.ly/1BbjrXg$, $http://bit.ly/1AaL4BT$. The testers provided their assessments via a questionnaire containing multiple questions for evaluating the quality of the videos and the results of the survey are shown in Table 4.4. The survey responses clearly indicate that, by employing the bandwidth adaptation strategies as explained in this chapter, the system is indeed able to perform satisfactorily under low-bandwidth environments. The movement smoothness and the image clarity were unanimously assessed to be much better in the case of adaptive streaming and thus the developed system is favoured to be used in such constrained conditions.

Table 4.4: Survey response on recorded trial videos

	Average Number of Taps Seen		**Video Clarity** [1(min)-5(max)]		**Movement Smoothness** [1(min)-5(max)]	
	Adaptive	Manual	Adaptive	Manual	Adaptive	Manual
Finger-tap motion (Fine Motor)	10 (True value=10)	7 (True value=10)	5	2	4.5	1.7
Elbow flexion-extension motion (Gross Motor)	5 full + 1 half (True value=5+1)	4 full + 2 half (True value=5+1)	4.8	2.2	4.5	1.2

4.5 Summary

The design and development of a Telerehabilitation system for PT/OT consultation is presented in this chapter, based on the frameworks formulated in Chapter 2 and 3. A new method for bandwidth adaptation was introduced and different consultation categories were identified based on the different requirements of a Telerehabilitation session. Each consultation category was formed with varying parameter settings such as frame rate, compression quality, colour information, cropping features, and spatial data extraction. The developed system was evaluated for the minimum bandwidth required to be used in a teleconsultation successfully, and it was shown to be able to operate even when the network speed dropped below 128 kbps. The efficiency of the bandwidth adaptation algorithm was tested and verified by abruptly changing the available network speed. The system was also tested for its efficiency in utilising the maximum available bandwidth and was able to exploit more than 95% of the available speed. Evidences from the experimental results as well as the ground survey responses suggest that, it is potentially possible to conduct satisfactory Telerehabilitation sessions using the developed system in bandwidth limited environments.

Chapter 5

Improved Telerehabilitation Framework with Additional Functionality

5.1 Introduction

As mentioned in Chapter 4, Telerehabilitation is an easy tool to provide equitable access to rehabilitation services for individuals who are remote from rehabilitation specialists, or those who are isolated as a result of a physical impairment which prevents them from attending local services [34]. A general physical rehabilitation session includes different kinds of tests and the therapist may need to quantify different body joint parameters of the patient, such as the joint position, inter-segment angle, etc. It is a challenging and lengthy process to measure these parameters even with assistance, as the patient needs to maintain a still position until the measurement is manually taken. This chapter describes an improved rehabilitation framework to help therapists carry out physiotherapy assessments using Kinect, which can be integrated into the system described in Chapter 4. The system does not require any third party assistance in taking the measurements and the assessment can be performed faster when compared to manual measurement.

Traditional equipment for measuring joint angles and positions include goniometer, inclinometer, and measuring tape. Reliability of different types of goniometer measurements was studied by Rothstein et al. [72] who concluded that the intra-tester reliability was generally high, whereas inter-tester reliability was not as high in joint angle measurements even when all the testers were professional therapists. This is expected since the positioning of the equipment can differ from person to person and it is almost impossible to fix it at the same location across all measurements.

Another study conducted by Fortin et al. [75] concluded that quantifying body segment parameters directly on the person is a lengthy process and may affect the reliability of the measurements. They also mentioned that measurement of body angles or distances using static images is the most promising technique for assessing human posture since it is cheap, fast, and easy. The study also pointed out that the reliability and validity of posture indices calculated from photographs have not been demonstrated for all body segments and thus are not comprehensive.

With technological progress, more sophisticated instruments were used for measuring joint angles as well as movement velocity of different body parts. Some studies reported using wearable sensors such as accelerometers and gyroscopes attached to the patient's body for measuring the position, angle, velocity, and acceleration parameters while performing gait analysis [73] [74] [115]. Some studies are not able to analyse and present the data in real-time while others use real-time transmission of measured data by means of Bluetooth and other wireless protocols [116]. These studies also revealed that acceleration patterns during gait can be used to deduce lower body posture.

Assessments using techniques of wearable sensors have the advantage of obtaining continuous measurement values as the patient can walk along a predefined stretch while the measurement is being taken. Moreover, once the patient wears the device, the therapist usually does not need to interfere during the exercise, thus eliminating the intra-tester measurement errors. However, the positioning of the sensor is vital in obtaining the accurate measurement values. A study conducted by Godfrey et al. [117] showed that a slight deviation from the original position can make a significant difference in the measured value from a gyroscope or accelerometer since the exact location of the accelerometer might influence the measurement accuracy. For instance, if the sensor is placed too close to the centre of rotation, the amplitude of the signal measured might be attenuated. The study also concludes that although multiple accelerometer arrangements enables to define more daily activities, these sensor arrangements are impractical for long-term monitoring and commercial use as it involves numerous cables running across the joints and along the body, and although wireless sensors may be an alternative, they will still have the other shortcomings mentioned above.

3D analysis systems are more recent methods developed for assessing the body joint and posture parameters without using wearable sensors, as demonstrated by Sawacha et al. [118] in which quantitative evaluation of kinematics (i.e. measuring body posture, joint angles, etc.) was performed using six cameras and reflective markers. A similar and even more accurate method is 4D Computed Tomography (CT) with a possibility of scanning the shoulder joint motion in real-time, as discussed by Alta et al. [119]. Although these systems can be accurate, the main drawbacks in this system are the high cost and the limited repeatability of the measurement. The system is highly complex and it can be very costly since multiple cameras are involved in the measurement. The positioning of the reflective markers limits the measurement repeatability, for a change in position can lead to measurement discrepancies. Some other interesting methods for human posture assessment such as flexible angular sensors and electromagnetic tracking systems are also discussed in a review study conducted by Rosario [120]. Most of these systems are cumbersome to house and transport, while some are expensive and require extensive technical expertise to operate and interpret which may not be readily accessible to the therapists.

This chapter presents the development and evaluation of an improved rehabilitation framework using the Microsoft Kinect sensor's skeleton tracking capabilities, which can be specifically helpful in Telemedicine systems. Skeleton tracking using Kinect has many advantages. It is marker-less and thus eliminates measurement errors caused by the positioning of the markers on the patient's body. Moreover, there are no sensors or wires attached to the body, enabling the patient to move freely. Many studies have been conducted on the possibility of utilising the Kinect's skeleton tracking mechanism for healthcare purpose and they have shown promising results on the usability of such systems.

Clark et al. studied the validity of Kinect for assessment of postural control [121] and they compared the results with the data from a 3D camera using reflective markers on the patient's body. The results were encouraging with the comparison yielding the Pearson's correlation coefficient values greater than 0.9 in the majority of the measurements, although the measurements did not include any specific joint angles or other rehabilitation specific tests. Another study conducted by Dutta [122] compared the Kinect measurements with the Vicon 3D motion capture system [123] as a gold standard. Although the Kinect measurement showed lesser accuracy than the Vicon system, the study concluded that, with a small amount of further development, Kinect may be used as a portable 3D motion capture system. The additional advantages the Kinect brings are its low cost, portability, as well as marker-less mechanism as compared to the other more accurate 3D systems [120].

Baena et al. also validated the upper and lower body joint motion data, captured using Kinect and compared it with the Vicon system [124] and the results were promising with a mean error rate relative to the range of motion averaging at 0.09. Kitsunezaki et al. developed a Kinect application for rehabilitation purposes with functions to measure different joint angles and to carry out some common rehabilitation exercises [125]. The study compared the Kinect measured data with that of an examiner who performed manual measurement on patients. The results revealed minimal differences between the two and concluded that Kinect can indeed be utilised effectively for real-time measurement of body joints in rehabilitation environment. Sato et al. conducted a recent study focusing on the effect of Kinect based exercises on healthy individuals in an experiment [126]. The results of the study revealed that Kinect based rehabilitation exercises significantly increased the individual's motivation in performing exercises and improved muscle strength and walking parameters in the elderly. Jintronix Inc (Montreal, Canada) developed a low-cost Virtual Reality (VR) rehabilitation gaming system that uses Kinect to track upper body movements [127]. The developed system was recently cleared by the Food and Drugs Authority (FDA 510(k)) to be used for Telerehabilitation purposes [128]. This is seen as a big step as far as the Telerehabilitation research using Kinect is concerned and gives a lot of confidence to the researchers to explore further on the potential of Kinect based rehabilitation efforts.

The work in this chapter presents an improved form of rehabilitation application framework, from that presented in Chapter 3, using Kinect which enables the therapists to monitor different body joint parameters in terms of linear and angular position, velocity, and acceleration as well as other complex measurements such as the centre of mass and moment of inertia of the human body parts. This chapter also explains the method to analyse and present the extracted data to the physician, leading to quicker diagnosis. Considering the high cost and complexity involved in implementing the existing systems to achieve similar objectives as mentioned earlier, it is necessary to develop a low-cost solution to assist the therapists in regular physiotherapy sessions. The framework presented here is very useful in this regard and offers the flexibility to perform the common rehabilitation assessments in practice today. Examples are provided in subsequent sections to demonstrate how traditional methods of rehabilitation assessments which sometimes require more than one therapist, can be automated using the developed framework. The developed framework also includes a database storage option to store the extracted data on a local computer which can be used for automated analysis and report generation to quantify the measured data. Although the accuracy may be slightly lesser when compared to more complex systems, Kinect based systems are much more acceptable with tolerable assessment accuracy, as seen in the evaluation section later on, especially when the benefits it brings in terms of portability, cost, and ease of use are considered.

5.2 System Design

The platform is designed such that the user can select the required joints and parameters to be tracked and the data will be plotted on the graph adjacent to the captured video display. The system is carefully designed to make it more generic such that it can be customised for assessment using standard rehabilitation practices. There are three main sections in the framework; parameter measurement, data analysis, and report generation.

5.2.1 Parameter Measurement

The parameter measurement section is further divided into different subgroups based on the type of the parameter measured; linear, angular, and joint distances tracking as well as other more specific categories which include measurement of the centre of mass and moment of inertia.

5.2.1.1 Linear Data Tracking

Linear data include position, velocity, and acceleration measurements. The user is also given the freedom to choose between X, Y, Z, or absolute value in the

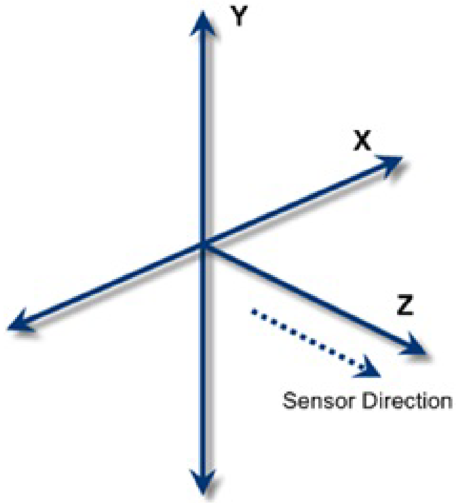


Figure 5.1: Kinect's coordinate system [6]

linear coordinate system as shown in Fig. 5.1, where the origin is the Kinect's position by default [6]. To select the joint to be tracked, the user has to click on the particular joint in the image, displaying the complete skeleton, provided with the program and the selected joint will be highlighted with a red square box in the image. Once a skeleton is detected in the frame, the program continues to track the joint and the live video will reflect the selection with red circles over selected joints over the patients respective body parts as shown in Fig. 5.2. The selected joint names will be displayed in the adjacent textbox as well. An option is provided in the program screen so that the skeleton position can be chosen either as seated or default mode (standing), depending on the situation.

The Kinect tracks the (X, Y, Z) coordinate values of the selected joint in terms of metres and feedback to the computer. Based on the selection, the program will plot the absolute value or X, Y, or Z value of the extracted joint coordinates. An option is also provided to let the user make a particular position as a reference since it is useful while measuring stretch distances as explained in the example measurements in Section 5.3. A timer is set-up to calculate

Figure 5.2: System being operated while linear data tracking is activated

the velocity, based on the position data between two subsequent time instances, as explained in Chapter 3. Similarly, another timer is set up to measure the acceleration based on two subsequent velocity values.

The extracted and calculated data will be plotted using a dynamic data display (D3) plot [97] in the program window and the measured data can optionally be stored in the local hard disk using the server-less self-contained SQL database engine SQLite [129], for further automated analysis by the program. Figure 5.2 shows the program being operated while tracking the selected joint positions.

5.2.1.2 Angular Data Tracking

In this category, three joints are to be chosen and the joint angle will be calculated based on the coordinate information of three joint positions returned from the Kinect. In Fig. 5.3, three joints are chosen on the left hand to measure the elbow flexion angle, as marked by the circles. Based on the selection, if A

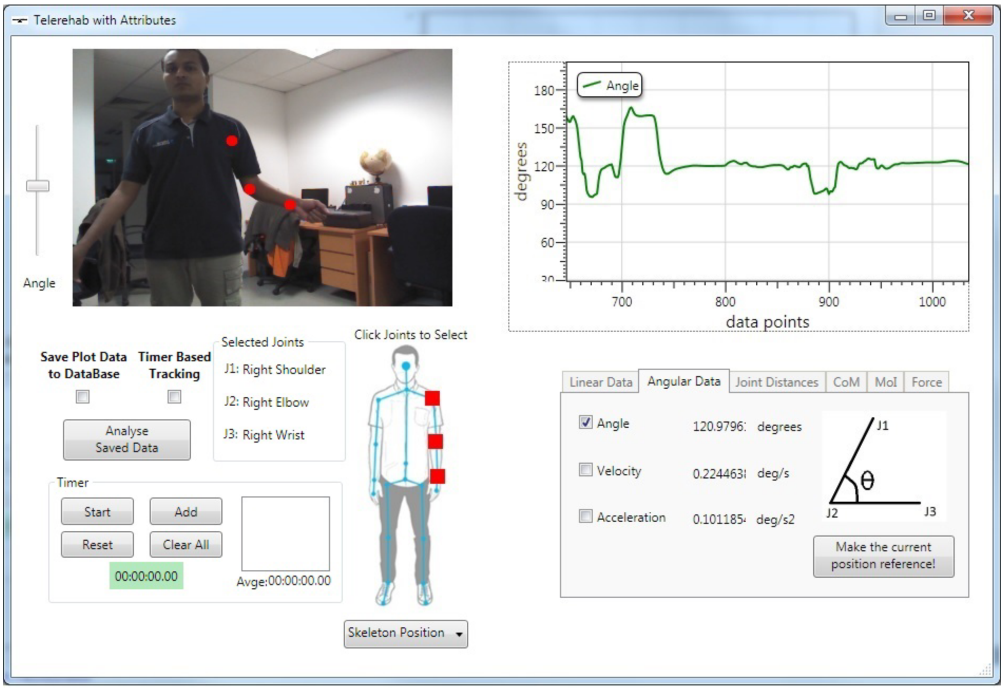


Figure 5.3: System being operated while angular data tracking is activated

is the vector formed from the elbow joint to shoulder joint and B is the vector formed from the elbow joint to the wrist joint, then the elbow angle that is formed between vectors A and B can be calculated as below which is derived from Eqn.3.6 in Chapter 3:

$$\theta = ArcCos(\frac{A \cdot B}{|A||B|}) \tag{5.1}$$

If a particular angle is to be set as a reference, an option is provided to the user to do so. Similar to the linear data, a timer is set up to measure the angular velocity based on subsequent angle values and corresponding time instances. Another timer is also set up to calculate the angular acceleration. The calculated angular data will be plotted on the graph and the data can optionally be stored in the local SQLite database.

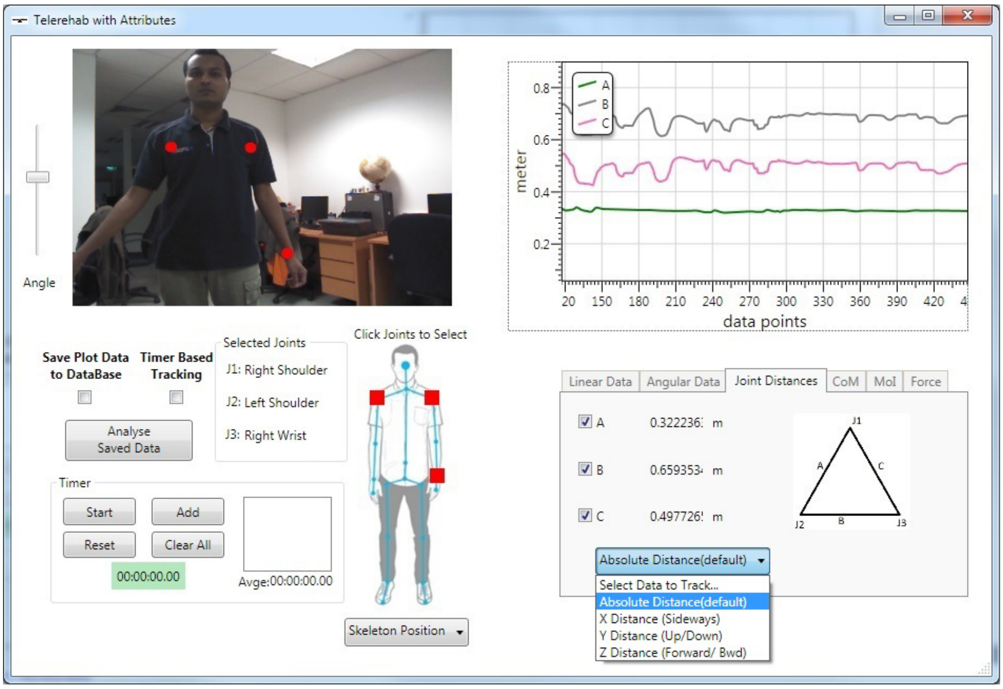


Figure 5.4: System being operated while joint distance tracking is activated

5.2.1.3 Joint Distances Tracking

This category is for tracking the absolute distances between joints. The calculation is purely based on the coordinate data feedback from the Kinect and the corresponding distances between joints 1, 2, and 3 will be continuously tracked and updated on the graph plot. Again, the user has the option to choose among absolute, X, Y, or Z distance between the joints. Distance tracking is useful for a therapist while monitoring the stretch distances that the patient is able to reach with regard to a specific body joint. This can also be used to track the step length while the patient performs walking exercise. Step length is an important parameter of interest in patients [130] [131] and it is otherwise not an easy task to determine using 2D video or other traditional methods. Figure 5.4 shows the program while operated under distance tracking category.

5.2.1.4 Center of Mass (CoM) Measurement

CoM is a fictitious point where all the mass is considered to be concentrated and it is an important indicator of human motion stability while performing exercises, walking, or standing [132]. CoM is estimated using the segmental method in this system. In segmental method, the location of each segment's (leg, hand, trunk, etc) CoM is expressed as a percentage of the distance from its proximal and distal endpoints. The segmental mass is also expressed as a percentage of the total body mass. Thus, once the exact joint positions are known, it is possible to calculate the corresponding centre of mass using the anthropometry table provided by Winter [133].

CoM measurements can be made for individual body parts or the whole body, depending on the need of the exercise being performed. In this platform, the user is given the option to select either to track full body, entire leg, or entire arm CoM and the corresponding CoM position will be highlighted in the video frame continuously as the patient moves around. The CoM position with reference to the Kinect will also be plotted on the graph provided. Figure 5.5 shows the developed platform in operation while full body CoM of the patient is tracked during an exercise routine. The user is also given the option to choose to track X, Y, Z, or absolute position of the calculated CoM. There is an option given to select the reference position if the user wants to fix it at a particular position. If no reference is selected, the Kinect sensor's position will be taken as the reference position (origin) as in Fig. 5.1.

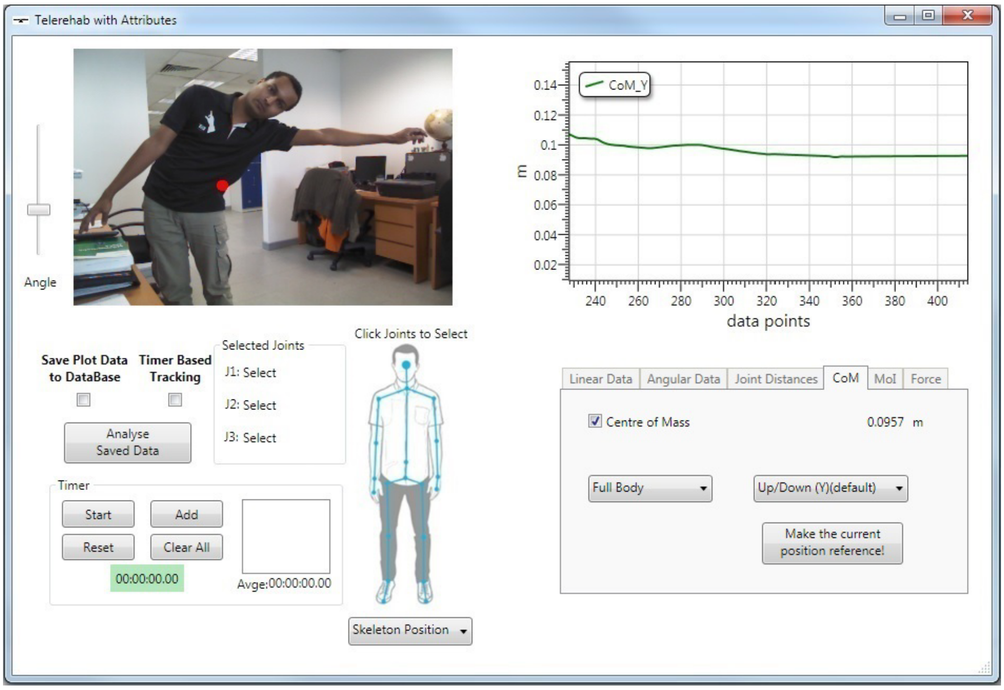


Figure 5.5: System being operated while full body CoM tracking is activated

5.2.2 Data Analysis & Report Generation

Once the data collection is done in the main program window, the user can analyse the saved data in the local database by clicking on the Analyse Saved Data button. A new window will appear as shown in Fig. 5.6 and the user can choose the data to be analysed. Moment of Inertia (MoI) data recorded while doing an arm motion cycle is chosen in Fig. 5.6 to demonstrate the analysis (more details on the MoI data extraction will be explained in Section 5.3.5). Once the user checks the corresponding checkbox, the saved data will be plotted on the graph on the screen. The user has the freedom to move the plot around in X and Y axes until the graph screen displays only the desired data to be analysed.

Once the proper data range is chosen in the display, the next step is to choose the parameters to be analysed. In the example shown in Fig. 5.6, a

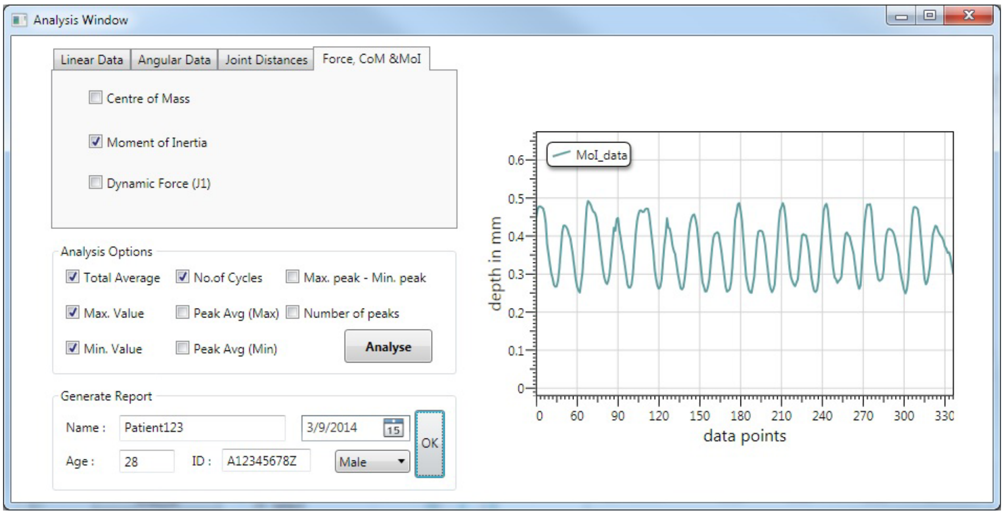


Figure 5.6: Data analysis window in operation

number of analysis options are selected and by clicking the "Analyse" button, these parameters will be analysed. In order to generate the analysis report, the user has to enter the patient details in the analysis window in Fig. 5.6. Clicking the "OK" button in Fig. 5.6 will generate the report in the predefined template created in the program. As shown in Fig. 5.7, the report will display the patient details as well as the analysed data together with a screen capture of the plotted data. The report can be saved in PDF, MS Word, or MS Excel formats for future reference. This data analysis helps the therapist to quantify the measured data and to easily monitor the patient's progress over multiple consultation sessions.

5.3 Standard Rehabilitation Assessments using the Platform

As the developed system is designed to be a general platform for rehabilitation assessments, it is the main objective for the system to be efficiently customisable to perform the various standardised tests in current practice. This

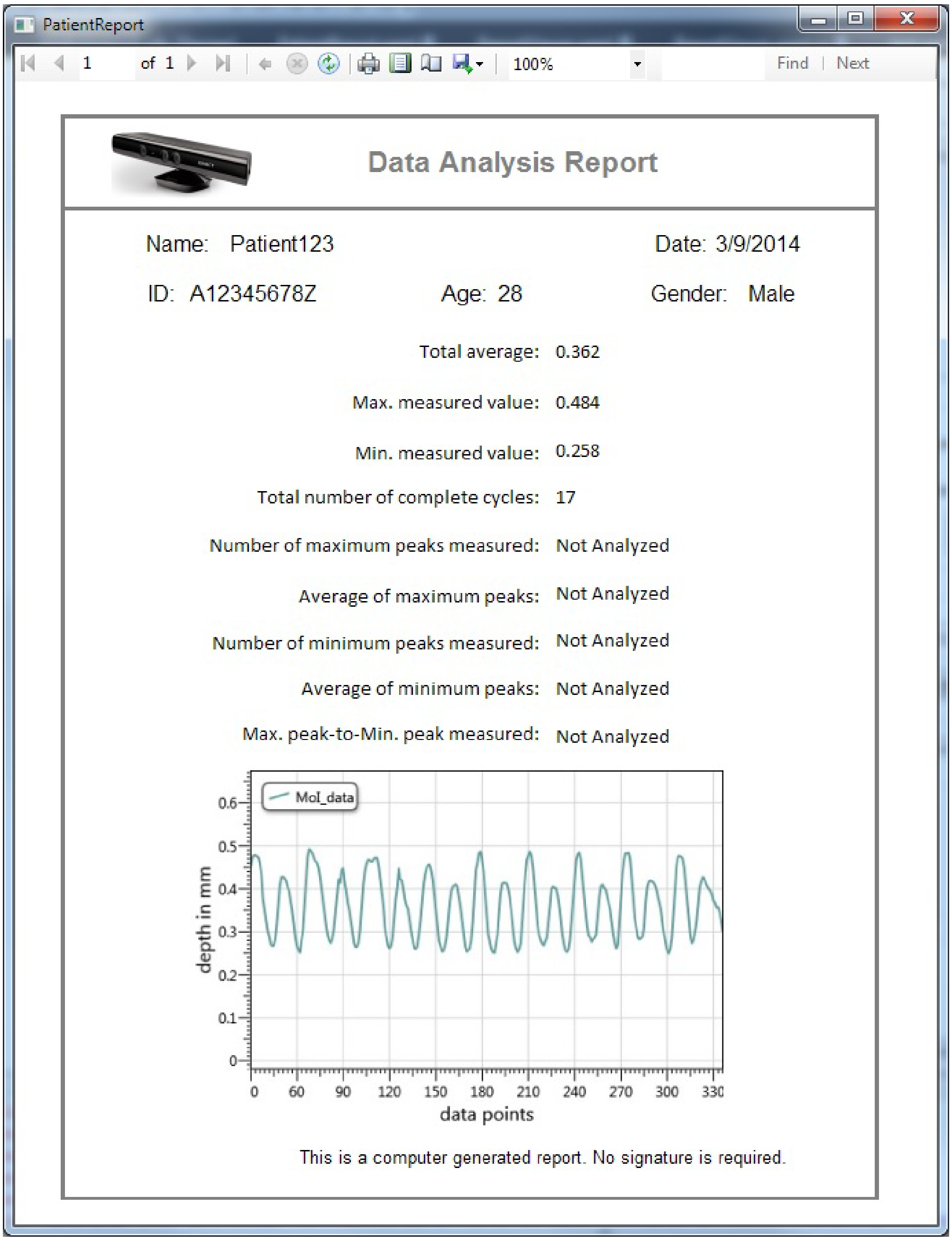


Figure 5.7: Analysis report generated by the program

section introduces some of the common tests that are widely used in current rehabilitation practices and shows how the developed framework can be used to perform those tasks.

5.3.1 Timed Up and Go (TUG) Test

TUG is a simple and quick functional mobility test that requires a subject to stand up, walk 3m, turn, walk back, and sit down [134]. The time taken to complete the test will be recorded and validated by the therapist. In a traditional setting, the therapist marks the 3 metres walking stretch for the patient and uses a timer-watch to do the assessment.

In this system, a timer function is available in the platform to achieve these kinds of assessment requirements. If the 'Timer Based Tracking' is activated, the graph data plotting will only be functional when the timer is running. The examiner can choose to track the patient's hip/spine position, under the linear data tab. While the patient is in the starting position (i.e. when the patient is in the chair), the therapist may make that position as reference by clicking the button so that the position data will be zeroed at that point. Once the patient is ready, starting the timer will plot the selected joint position on the graph. Once the patient completes one cycle and returns back to the sitting position, the timer has to be stopped. The peak value of the graph plot will show the distance covered by the patient and the therapist can determine whether the required 3m distance is covered by the patient. If multiple tests are required, the therapist can record the measured timer value by clicking the 'Add' button in the timer box provided and reset the timer to continue with the next cycle. As more runs are recorded, the average measured time will be shown by the program

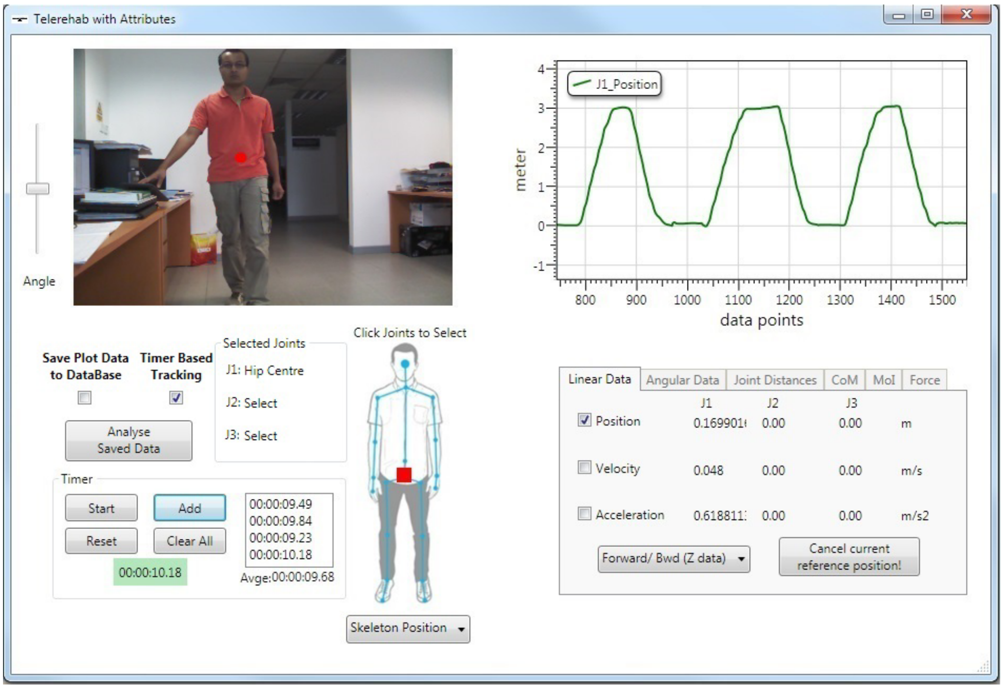


Figure 5.8: Timed Up and Go test performed using the developed platform

at the bottom of the timer box. Figure 5.8 shows the developed platform being used for the TUG test which shows multiple run results with the averaged time and the graph plot of the covered distance. Here, Z data is chosen to be tracked since the subject is moving in forward/backward direction relative to Kinect, with the chair placed behind the subject. The user can also choose to track the X data if the subject moves in parallel to the Kinect sensor.

5.3.2 Sit-to-Stand Test (SST)

SST is commonly used to assess the lower extremity strength and balance for people with arthritis, renal disease, as well as older adults. The test is also used as an indicator of postural control, fall risk, and as a measure of disability. In this test, the patient is asked to rise from a standard chair and sit down for a fixed number of times and the time is recorded [135]. Similar to the TUG test, the timer can be made use of while the patient's full body CoM is continually

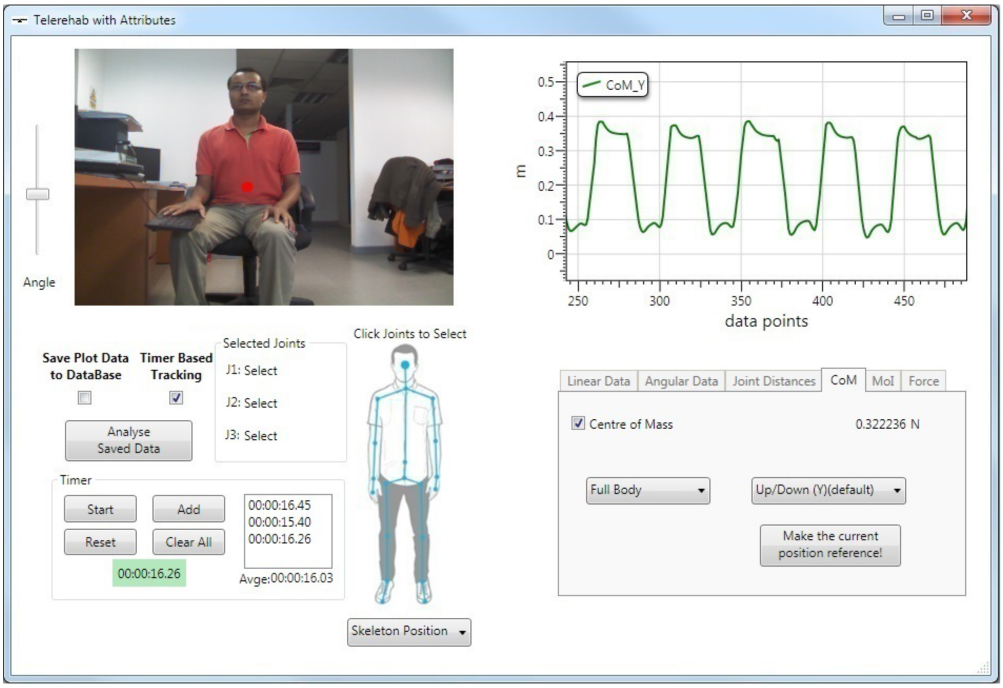


Figure 5.9: Sit-to-Stand Test performed using the developed platform

tracked and recorded on the graph plot. CoM is chosen in this case as it can be an added indicator of motion stability while performing exercises. The graph plot clearly displays the number of cycles performed by the patient and the smoothness of the CoM movement. The platform can also be customised to measure other body joint position while performing the SST. Figure 5.9 shows the program window while the platform is being used for SST.

5.3.3 Functional Reach Test (FRT)

FRT is a clinically accessible measure of balance in which the difference between arm's length and maximal forward reach is calculated, with a fixed base position [136]. In the traditional method, the patient has to stand with one arm in forward position, forming a right angle between the arm and the trunk while the therapist notes down the exact position of the hand. When the patient stretches the arm forward to the maximum, the therapist notes down the position

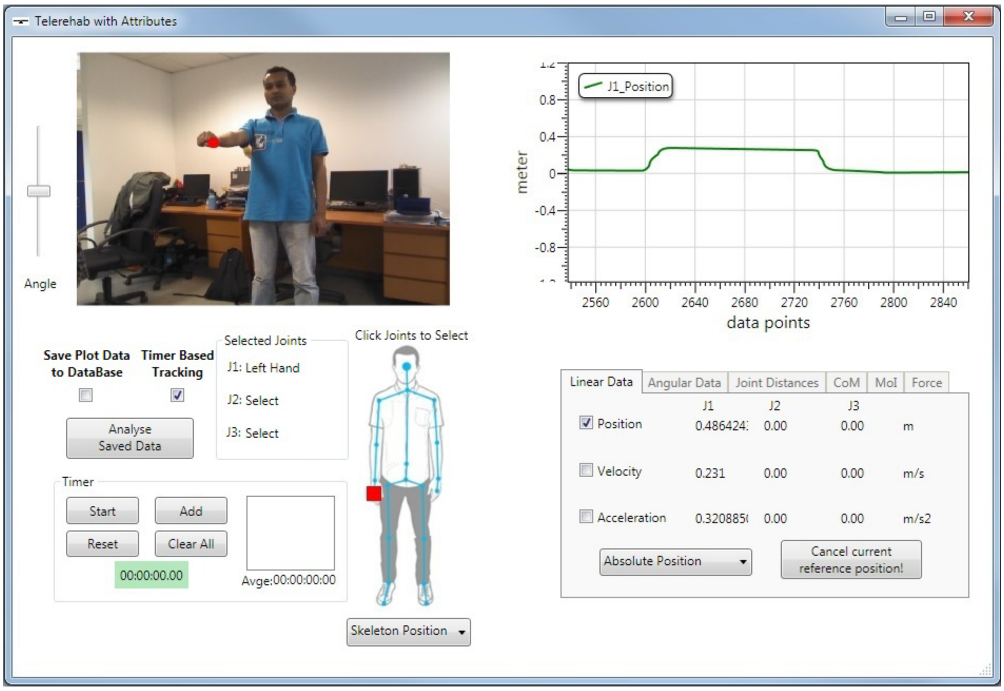


Figure 5.10: Performing Functional Reach Test using the platform

again and calculate the total stretch length, which is the difference between the two. This gives the functional reach of the patient and it is normally conducted while the patient stands in parallel to a wall for ease of noting down the arm positions and it is a time consuming procedure in traditional settings.

FRT test can be performed easily using the developed platform by making use of the linear data tracking of the body joint. The user has to select the body joint such that the patient's hand position is tracked. Once the patient is at the initial position, the therapist can make that position as reference by clicking the button and the stretch performed by the patient will be tracked by the Kinect continuously and plotted on the graph, which indicates the functional reach of the patient. Figure 5.10 shows the program screen when the FRT is being performed by the patient.

5.3.4 Performance Oriented Mobility Assessment (POMA) for Gait

The system can also be set up to see the trend in gait performance while the subject performs the exercise, thereby enabling it to be used for POMA, which is a standard, performance-based test to measure balance and gait in older adults [137]. POMA for gait, or POMA-G, involves a number of steps, out of which many can be performed by tracking the step length of the patient with the help of Kinect. To do this, the therapist has to select the joint distance category and track the distance between the left and right ankles or feet. Based on the data plot from the step length tracking, it can be assessed for symmetry, step continuity, initial hesitancy etc. In Figure 5.11, the subject can be seen performing a walking exercise while being assessed for POMA-G. The subject was instructed to walk forward 3 metres and turn back and return to the starting position at the normal speed. The X-distance of the step length is tracked and the smooth waveform, with similar peak magnitudes in positive and negative directions in this case, indicates the step continuity with symmetry and the even distribution of the data in terms of frequency implies the continuity without any initial hesitancy while performing the exercise.

Figure 5.12 shows the extracted data plots while performing POMA-G on a patient with walking disability. In Fig. 5.12(a), the subject walks without symmetry in step length, i.e. being unable to pass the swing foot (left) beyond the stance foot (right). While capturing the X-distance of the step length, this is clearly evident from the graph since only positive values are seen here. Figure 5.12(b) is the data plot of the linear data extracted while tracking the Z-position

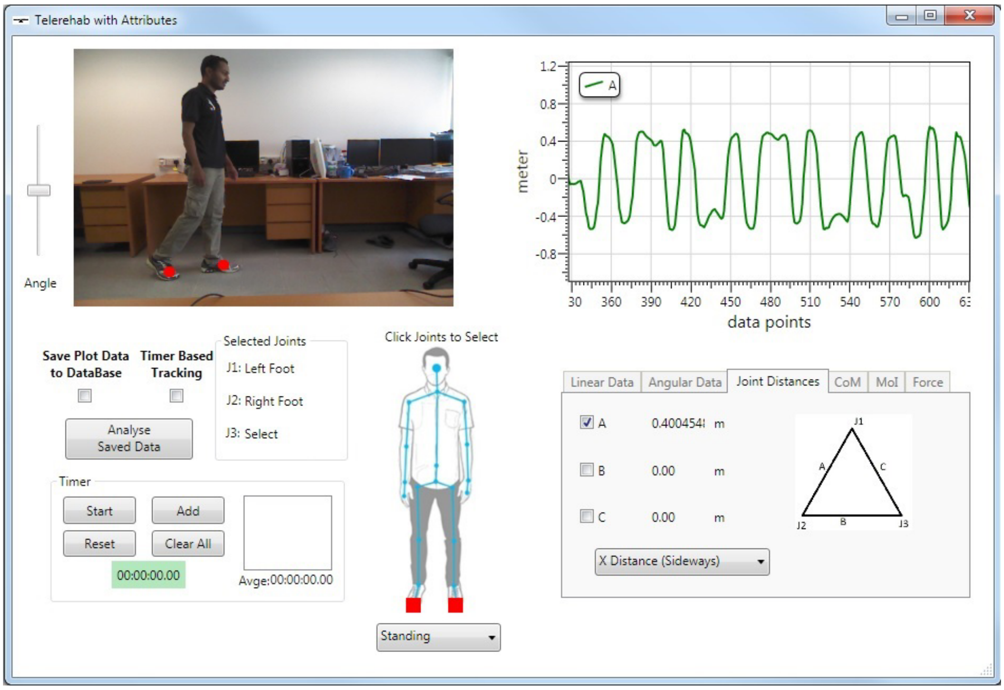
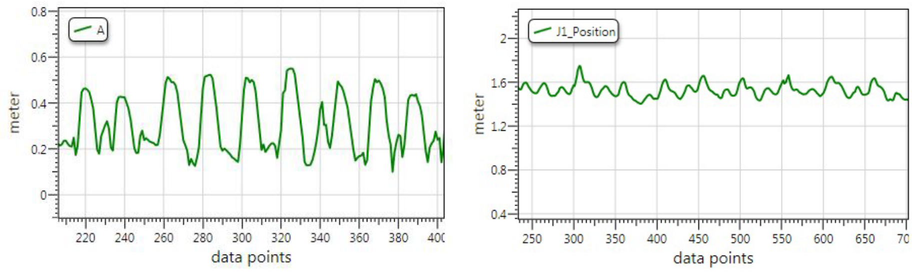


Figure 5.11: POMA-G assessment by tracking the step length



(a) asymmetric walking (b) path deviation while walking

Figure 5.12: POMA-G data for walking

of the spine while walking along a straight line. The inconsistency in the data is an implication of the path deviation the subject experiences while walking, which is one of the performance indicators in POMA-G.

One thing to note however is that, different measurement categories were used, i.e. linear data and joint distance categories, while performing POMA-G. Thus, without a tab for selecting these common tests, the therapist may need to perform multiple runs to complete the session. Due to this reason, a new tab is created to have common tests such as TUG, SST, and POMA-G with

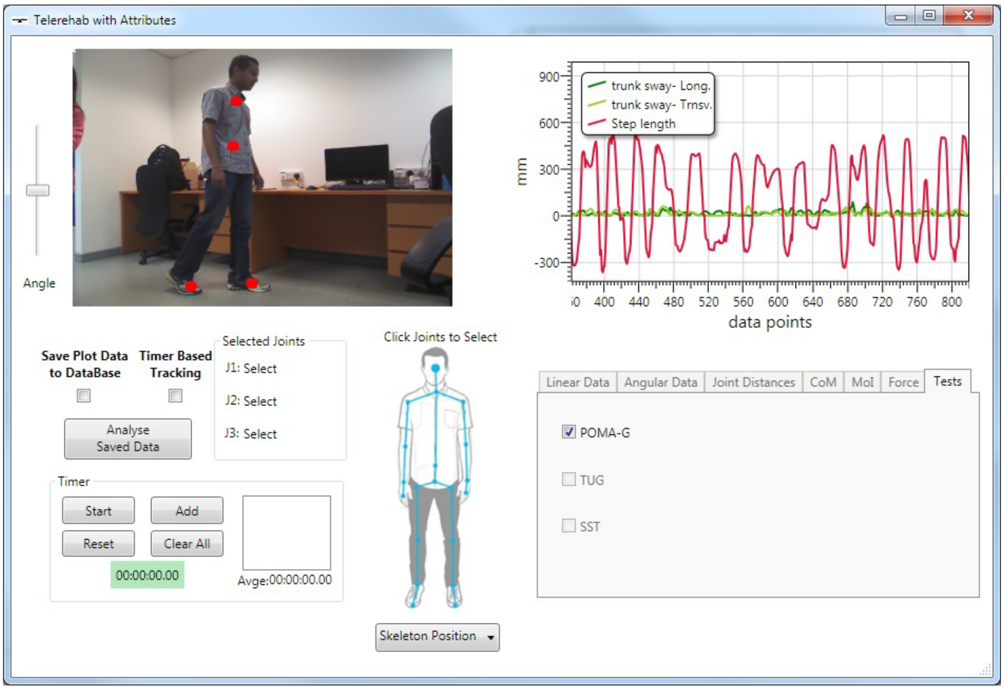


Figure 5.13: Platform being used for POMA-G assessment

readily selected joints and other necessary parameters for measurement purpose. Here, selecting POMA-G will track and measure the step length as well as the longitudinal and transverse sway of the body trunk while the subject performs the exercise. The trunk sway is detected based on the Kinect feedback on the subject's spine and shoulder centre position data. Figure 5.13 shows the program window while POMA-G test is selected. As mentioned earlier, the system cannot be used to assess some specific parameters in the POMA such as the step height since this will require the measurement of the floor height, which the Kinect is not capable of. Another limitation in this test is that the patient has to restrict the walking space within the visibility of the camera which cannot be more than 5-6 metres in general.

5.3.5 Other Tests

The developed platform can also be used in other rehabilitation assessment scenarios to easily quantify the measurements in terms of time, position, angle, velocity, acceleration, etc. The platform can be used for tests such as Berg Balance Test which involves many timed tests while the subject performs single leg stance, sit-to-stand cycles, etc. Similarly, the platform can also be utilised to measure stretching positions and to assess whether the patient is making progress across consecutive rehabilitation sessions by recording the plotted data. Another option which is available on the platform is to measure the Moment of Inertia (MoI), which is usually done in healthy individuals, as part of sports rehabilitation. MoI (represented by I) is the angular equivalent of mass and it gives an indication of how difficult it will be to rotate an object, in this case using body parts such as arms and legs. MoI about the centre of mass of an object with mass m can be calculated as:

$$I_0 = m\rho_0^2 \tag{5.2}$$

where ρ_0 is the distance from the axis of rotation to the CoM, also known as the radius of gyration. In the case of a human body, as most body segments do not rotate about their mass centre, but rather about the joint at either end, MoI measurements about the joint centre is calculated using parallel-axis theorem as:

$$I = I_0 + mx^2 \tag{5.3}$$

where x is the distance of between CoM and centre of rotation of the joint

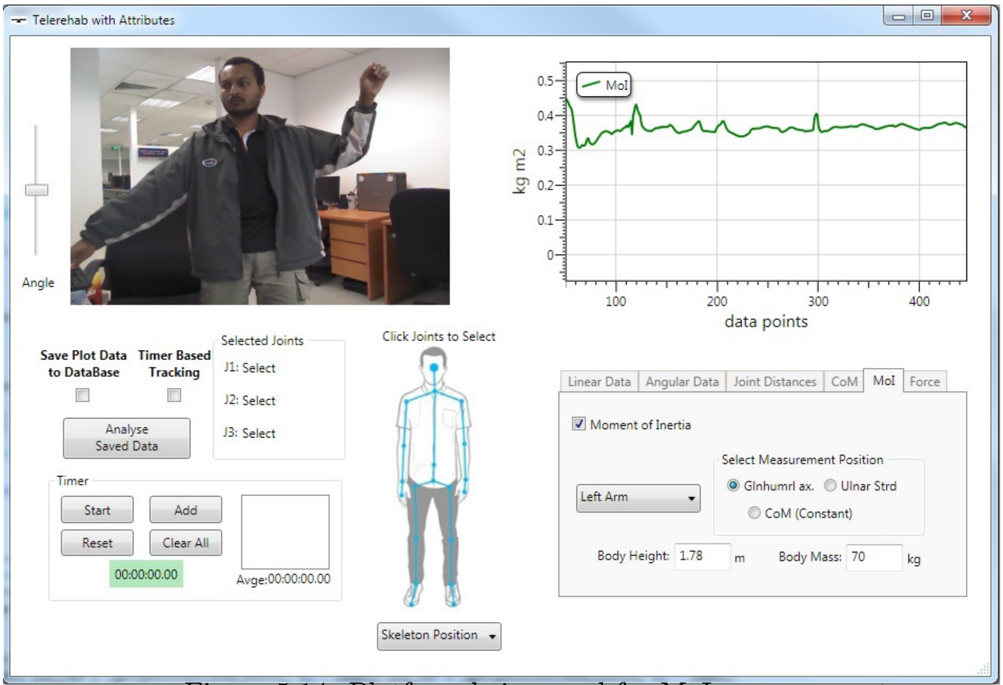


Figure 5.14: Platform being used for MoI measurement

[133] [138].

This platform measures MoI based on the data in the anthropometry table provided by Winter [133] as well as the CoM measurement as explained in the previous section. The user is given options to choose from different body segments and options are provided to choose the measurement point for each segment. For example, if the user chooses left arm as the segment, further options are given to choose the measurement point as shown in Fig. 5.14. The user is also required to key in the height and weight of the patient under assessment and the system continuously calculates the MoI value as the patient moves the body segment and plots the data on the graph.

5.4 Evaluation

The system had to be evaluated to see how well the implemented categories performed while tracking the joints and calculating the segment angles when compared to the traditional methods. First, the accuracy of angle measurement was tested by comparing with a goniometer reading. The system was further tested while carrying out standard rehabilitation assessments of TUG test and FRT and compared with results from traditional measurements.

5.4.1 Angle Measurement Accuracy

The data measured by the system were validated by comparing it with a traditional method currently used by therapists. An electronic goniometer, which was calibrated for accuracy, was chosen for comparison while measuring the elbow and knee angles using the Kinect. The goniometer was connected to the patient's elbow as shown in Fig. 5.15. A LabVIEW program was used to extract the goniometer data. Three able bodied subjects were used for data collection and the extracted data were used to calculate the Pearson's correlation coefficient, R, a common test to measure the strength of the linear association between two sets of continuous data, where a value of 1 means perfect positive correlation and 0 means no correlation [139]. The slope of the XY-scatter graph using the two measurements was also used to determine the resemblance between the two.

Both the LabVIEW program and the developed program (under 'Angular Data' tab) were running in parallel and measurements were collected at random elbow positions between 50 degrees and 175 degrees. Upon comparison, the

Figure 5.15: Angle measurement setup using electronic goniometer

Pearson's correlation coefficient, R, is measured to be 0.97 on average, which indicates a very strong correlation between the data sets. The slope value is measured to be 1.04, which indicates that the regression line is indeed very close to the 1:1 ideal regression line. Figure 5.16 shows the XY-scatter plot from one of the data collection experiments conducted with the trend line approximating the slope of the presented data. The horizontal axis represents the Kinect's readings and the vertical axis represents the goniometer readings. Both measurement units are angle measurements in degrees and the trend line is shown in the graph using the solid line. It can be seen from the graph that the measurements are more precise and accurate at lower and higher angle readings, but tend to be more scattered in the middle. This is due to the inherent limitation of Kinect in which it is not accurately able to track the joints when the body joint is obstructed by other body parts. Moreover, it was reported that the Kinects stability of the body geometry varies when the orientation is changed. For example, the bone length may vary from 2cm to 5cm when the body is in frontal view and 45 degree view respectively [140]. Table 5.1 presents the average values of correlation coefficients and slopes based on the data from elbow

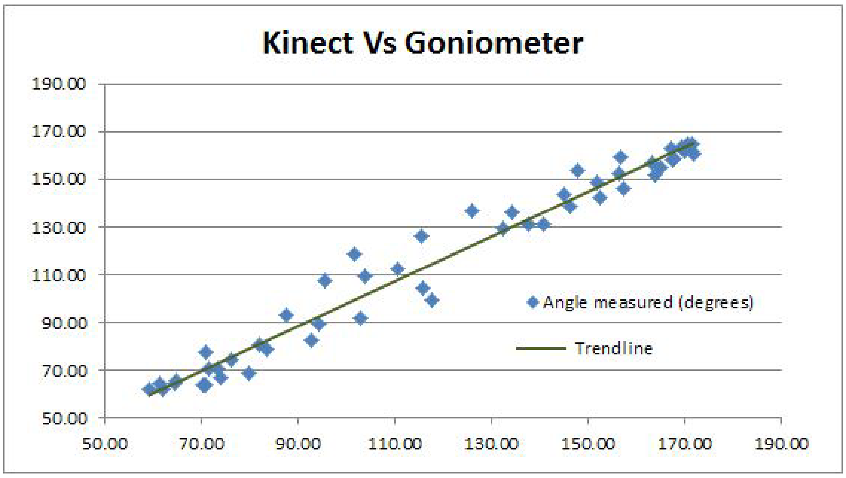


Figure 5.16: XY-scatter diagram of Kinect and goniometer measurement data

Table 5.1: Experiment data on angle measurement from three subjects

Subject#	**Pearson's correlation coefficient, R**	**Slope of trend line**
1	0.98	1.18
2	0.97	0.94
3	0.94	1.01

measurement for three subjects and it is evident from these results that both the sets of measurements are very close to each other.

5.4.2 Accuracy of Standard Rehabilitation Tests

In order to evaluate the assessment accuracy while performing standard rehabilitation assessments using the developed platform, TUG test and FRT were considered. The test subject was a healthy individual and prior consent was obtained before requesting to perform the required tests. The evaluators were technical experts who were briefed on the evaluation process and the criteria. The tests were carried out simultaneously via the manual method, using a watch timer and a measuring tape, and by using the developed system, with the testers located away from the subjects without any direct visual contact. Three sets of measurements were taken and the results are as shown in Table 5.2. The results show that the differences in the measured values are insignificantly small and thus the assessment method using the software is deemed to be sufficient. This is even more insignificant, considering the potential inter-rater differences possible in such a measurement scenario. One added advantage while performing the TUG test using the developed system was that, the tester was able to clearly see if the test subject covered the required walking distance of 3 metres merely by looking at the data plot, whereas in the manual method, the tester had to manually measure and mark the distance to be covered before the TUG is conducted. In addition, while using the developed system, the tester was able to measure the subject's step length as well by turning on the joint distance tracking function.

The developed Telerehabilitation framework was not compared to the other similar systems such as the one using Vicon systems due to the complexity involved in setting up the system as well as the need for a qualified therapist to interpret the data. Moreover, there are available studies on this comparison as mentioned in Section 5.1 [121] [122]. Another such study conducted by Stone and Skubic compared the results of gait assessment between a Kinect-based system and a webcam and Vicon motion capture systems [141]. The results showed good agreements in measurements and reassured Kinect's usability in such assessment scenarios. A similar study compared the use of Kinect with that of OptiTrack, a motion capture system, for stroke rehabilitation purpose [142]. The results recommended Kinect to be sufficiently accurate and responsive system with low latency for such purposes. Although there are disadvantages in terms of the angle of vision which limits the Kinect visual area, comparable results in assessments

Table 5.2: Assessment comparison between in-person method and software method

Trial #	TUG Test		FRT	
	In-person	Using software	In-person	Using software
1	10.24 Sec	10.44 Sec	32 cm	31 cm
2	8.67 Sec	8.96 Sec	31 cm	30.5 cm
3	9.36 Sec	9.85 Sec	42 cm	41 cm

combined with other advantages such as low cost, easy portability, etc. make Kinect ideal for such applications.

5.4.3 Limitations

The developed platform was validated to be reliable and accurate in the standard assessment scenarios as shown above. However, it has certain limitations as well. It is mainly limited due to the accuracy of Kinect itself. According to independent assessment, Kinect is measured to be accurate to around 1mm at 1 metre distance and the accuracy level would reach around 4 cm when the distance of the object tracked is 5 metres [101]. Similarly, another study pointed out Kinect's stability of the body geometry when the orientation is changed. For example, the bone length may vary from 2cm to 5cm when the body is in frontal view and 45 degree view, respectively [140], which means that, facing the Kinect while performing the exercise yields better measurement results. Another limitation is in the measurement of the CoM using the segmental method. In this, the mass percentage of individual body parts are taken based on the average table from previous studies and the actual mass percentage may vary among individual subjects. Thus the measured CoM may not be the true value, but an estimated value.

Similar limitations exist in the measurement of MoI as well since it is an estimated value based on the anthropometric table from Winter [133] and may differ from the true value. Another limitation due to the use of Kinect is that the rehabilitation session can only be performed indoors since the infrared rays from the sunlight may cause interference to the Kinect's skeleton detection (depth stream) and thus compromise the data measurement accuracy.

5.5 Summary

A much improved rehabilitation framework with an easy-to-use interface is presented in this chapter. Different categories were introduced to measure the linear and angular parameters of body joint motion, including position, velocity, and acceleration. The chapter also demonstrated how standard rehabilitation assessments such as FRT, SST, etc. can be customised using the developed platform. This system, which utilises the skeleton tracking ability of Microsoft's Kinect sensor to detect different body joints, was compared to the traditional method of joint angle measurement device using an electronic goniometer. The results showed very strong correlation between the two data sets and thus the new method introduced in this chapter was deemed to be acceptable. Measurements based on the new system were also compared to in-person methods using standard rehabilitation assessment tools such as TUG and FRT. The results again showed very close correlation and the difference in measurement results were found to be insignificant. The system developed for rehabilitation was thus evaluated to be potentially able to replace the traditional and other more complex and expensive devices for measuring body motion parameters, at least in the case of those assessment methods involving gross motor movements, as tested above.

As mentioned in the first chapter, while visual and spatial information plays a crucial role in Telerehabilitation, other physiological measurements, namely heart rate, breathing rate, temperature, etc., are vital in assessing the patient performance. Chapter 6 will present the integration of a readily available sensor package to measure the physiological parameters of the patient, while performing rehabilitation exercises, so that the physician can assess the patient's body response to the recommended exercise and make amendments to the prescribed exercise if necessary. Chapter 6 will also present the integration of the improved framework presented in this chapter with the existing Telerehabilitation system presented in Chapter 4, in order to make the overall system more comprehensive.

Chapter 6

System Integration

6.1 Introduction

The developed Telerehabilitation system presented in earlier chapters is mainly for audio-visual data transmission with the capability to quantify physical exercise data based on the Kinect sensor feedback. However, the system lacks the capability to measure physiological data which can be key indicators of a patient's health while performing the rehabilitation exercises, especially when the Telerehabilitation session involves a patient with a history of acute illness. Examination of physiological signs such as heart rate, respiration rate, body temperature, etc. provide the physician/therapist with important data about the status of the cardiovascular/ pulmonary system, which are key indicators of the body's response to the prescribed physical activity [76]. This is an important add-on to consider and this kind of sensor is necessary for home based Telemedicine systems since the remote doctor has limited options for measuring the patient's vital signals. One way to address this shortcoming is to enhance the system with some easy-to-use sensors using which, basic physiological signals like temperature, heart rate, respiration rate etc. can be extracted without the assistance of a third person.

It is decided that designing an entirely new sensor package would not be very productive in terms of time and effort since there are many existing sensors available to be bought off-the-shelf in the market. It would be much more sensible to make use of an already existing sensor package and find a way to communicate with the sensors through the .NET platform, which is the development base for the Telerehabilitation system. The addition of such a sensor package to monitor vital signs would enable the developed Telerehabilitation system to become more comprehensive in terms of its usability.

Due to the ease of availability as well as to keep the development cost to a minimum, only commercially available sensor units were considered as an add-on to the system. There are a number of sensor modules that are available in the market today, including VivoResponder from ViviMetrics [143], NuMetrex from Textronics [143], Sensium from Toumaz [144], BioHarness from Zephyr [145], and Sensor Electronic Module (SEM) from Equivital [7]. VivoResponder is a lightweight chest strap with sensors embedded in it to measure physiological parameters. NuMetrex is designed as clothes such as sports bras and men's base layer garments with incorporated sensor networks with biomedical devices linked to communication systems and display devices to monitor vital signs. Sensium is another healthcare product which comprises lightweight, wearable, single patient use patches that monitor patients' heart rate, respiration rate, and temperature every few minutes and wirelessly send those parameters to an attached station or any web enabled device. Zephyr's BioHarness is a small sensor module which can be strapped to the human body and monitors the user's heart rate and breathing while wirelessly relaying the data via Bluetooth. Similarly, SEM is another device that monitors a number of physiological parameters using a sensor module that is strapped around the human body and transmits the data out wirelessly through Bluetooth.

After considering the devices, including those mentioned above, it was concluded that the SEM from Equivital is most suited for the Telerehabilitation application in this case. SEM has built in sensors to measure numerous physiological parameters such as body temperature (both skin and internal), respiration rate, heart beat rate, ECG, as well as accelerometer and gyroscope sensors for activity level and orientation measurements etc. Moreover, Equivital comes with a Software Development Kit (SDK) for .NET and JAVA programming interfaces, which makes it ideal for integrating as an add-on package to the already developed Telerehabilitation interface which is originally based on .NET platform. This ensures seamless integration of the sensor into the existing system, without going through any third party wrappers for data access from the sensor. The sensor module also has built-in algorithms to calculate orientation status, fall detection, etc. using the raw data measured though the individual embedded components.

A number of research groups have worked on developing successful solutions for similar health monitoring purposes using the Equivital SEM. Neubert et al. developed a mobile real-time data acquisition system for application in preventive medicine using the SEM to be used in occupational health studies without influencing the subject's daily routines [146]. The captured data were transferred to a mobile device through Bluetooth communication and then sent out to a web-based remote monitoring device using the GSM network. The use was mainly for teams deployed in rescue missions or fire-fighting or even training purposes, so that their vital signs can be continuously monitored and any potential medical emergencies among the rescue team during the mission or training can be prevented. The research team chose SEM since it enabled the acquisition of cardiac functions, and pulmonary functions unlike many of the other sensors that were available in the market. The SEM was chosen also due to its light weight factor and ease of wearing while the subjects carried out their regular duties.

Another research team involving Banos et al. also used Equivital SEMs to design an Android based physiological data monitoring application, Physio-Droid, for use in continuous personal health monitoring of patients [147]. The platform was also designed to trigger alerts and emergency calls upon detecting abnormalities or risk situations. The application included data storage for further usage and presentation to the user in an easy-to-understand graphical plots and the application was designed such that it is compatible with any type of Bluetooth interface in Android devices. Again, the SEM package was considered due to its ease of implementation and the ability to monitor a number of useful physiological parameters which was superior when compared to other similar systems.

The works presented in this chapter are:

1. Integration and evaluation of an add-on sensor package to be used in the developed Telerehabilitation application for measuring the patient's physi-

ological data during the regular consultation sessions under home or clinical setting; and

2. Integration of the improved framework for performing Telerehabilitation assessments presented in Chapter 5 to the developed Telerehabilitation application.

Thus in this case, the application of the sensor module is assumed to be mainly in a controlled environment where the user has access to a PC or laptop with Bluetooth connectivity. The next section presents details of the Equivital SEM module and how the sensor is integrated into the existing platform.

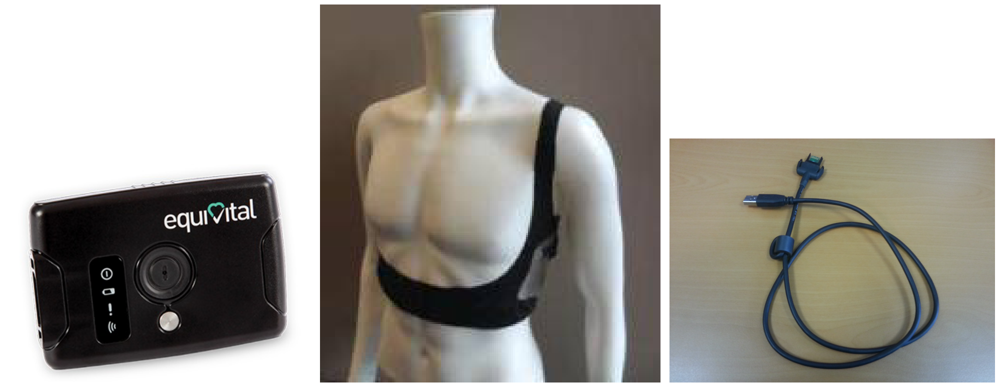
6.2 Equivital Sensor System Overview

6.2.1 Sensor Set-up

The Equivital sensor system consists of the EQ02 LifeMonitor device or SEM that measures and transmits the data out through Bluetooth, Equivital belt that contains the SEM and strapped around the patient's body, and a USB cable to connect from SEM to PC for the initial set-up purpose as well as for charging the SEM battery. The whole system is very light in weight with the SEM weighing around 40 grams and the belt weighing around 120 grams. Refer to Appendix A at the end of this thesis for the detailed SEM specifications. The SEM has an on/off button and some LED indicators to indicate battery status, Bluetooth activity status, and another one to indicate events and alerts. The belt also has a connector for linking it up to the SEM so that other measurements such as ECG, respiration rate, etc. that are measured using the sensors embedded in the belt can be transmitted over to the connected device. SEM has a built-in Bluetooth transceiver which transmits data continuously out to the connected device, which in this case is the PC/laptop running the Telerehabilitation application. The PC is recommended to run Windows 7 operating system with at least 1GB RAM capacity in order for the EQ02 LifeMonitor SEM to function smoothly. Figure 6.1 shows the contents of the Equivital sensor system.

A freely available software, Equivital Manager, is used to connect up the SEM to the PC using the USB cable for initial configuration. This includes synchronising the timer in the sensor with the PC time, setting the limits for different measurement parameters so that the alarm is activated once the sensor reading goes out of these limits. There are two modes of data transfer in SEM; partial and full disclosure modes. In partial disclosure mode, which is also known as the summary disclosure mode, data such as respiration rate, skin temperature heart rates, etc. are transmitted once every 15 seconds and ECG, respiration rate, and other sensor alarms are transmitted once every 5 seconds. In full disclosure mode, the SEM will output all the summary disclosure data together with the complete raw data for ECG and accelerometer sensors at around 256 Hz range which can be used to plot the waveforms for monitoring purpose. The disclosure mode can be set using the Equivital Manager software or programmatically using the SDK [8]. Figure 6.2 shows the configuration page of the Equivital Manager with the SEM connected.

There are a number of other sensors that can be added onto the basic SEM package described above. These sensors include GPS module, core temperature capsule, galvanic skin response sensor, SpO2 pulse oximeter etc. Addition



(a) Sensor Electronic Module (SEM) (b) Sensor belt (c) USB connector cable

Figure 6.1: Equivital sensor system [7]

of these sensors as well as other third party complementary sensors allows the Equivital sensor system to become a complete Body Area Network (BAN) and transmit their information to the SEM while being automatically integrated into the real-time data stream. However, due to cost constraints, this Telerehabilitation application does not make use of any complementary sensors and limits the measurements to those equipped in the basic package. In case needed, the user always has the option to add on the sensor later on and trace the sensor feedback from SEM as the parameters will be already included in the library file used in the application.

6.2.2 Measured Parameters and Built-in Algorithms

As mentioned earlier, Equivital SEM module is capable of measuring a number of physiological signals from the human body. The belt contains 2-lead electrodes to measure the ECG signals and a piezoelectric material which is used to measure the respiration rate based on the expansion of the elastic strip as the material's resistance value changes accordingly. This is calculated as a 60 second rolling average value, reported every 15 seconds. The accelerometer and

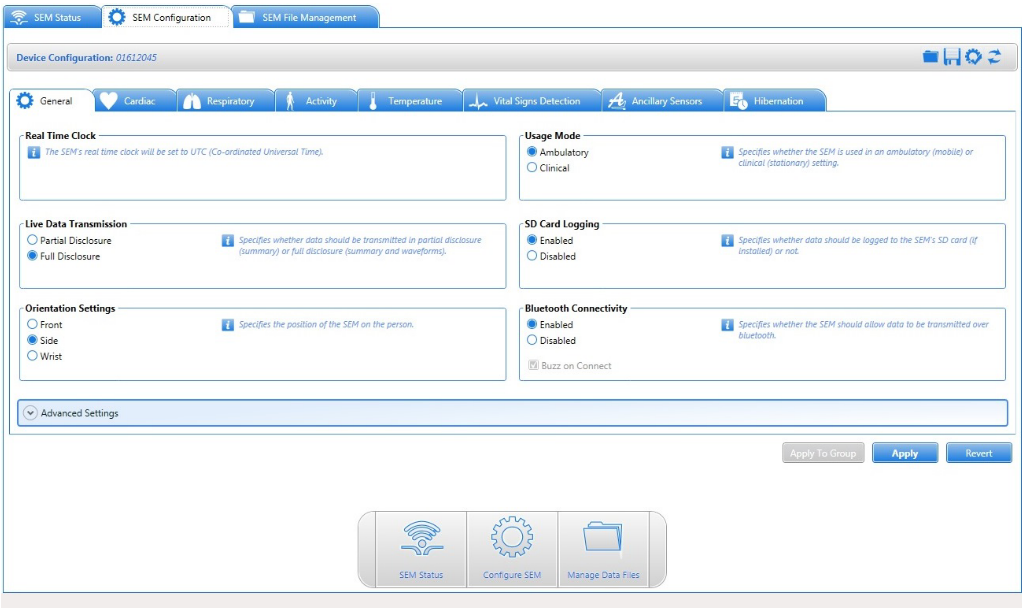


Figure 6.2: Equivital Manager with SEM connected for initial configuration [8]

gyroscope are used for the measurement of movement patterns and orientation and are built-in to the SEM itself. Similarly the skin temperature sensor is also measured using the infrared thermistor embedded in the SEM itself, which will be in contact with the patient's chest once the belt is worn. Resolution of the measured temperature is 0.1°C and it is updated once every 15 seconds, in default setting. For all the measured parameters derived based on raw sensor data, the SEM also provides a signal confidence value (in the range 0-100) to indicate the quality of the measured signal [8].

One key advantage of the Equivital SEM system is the built-in algorithms that are embedded in the device to analyse the collected raw data and output meaningful messages and parameters that are derived based on the measured data simultaneously at frequent intervals. For example, based on the accelerometer and gyroscope data, the SEM is able to detect a free fall using its built-in algorithm. Another algorithm makes use of the raw ECG data and derive heart rate (based on a 30 second rolling average) as well as the R-R interval (the time between the wave-peaks of the recorded ECG wave). The algorithm is also able to detect irregular rhythms, low/high heart rates and alert in case the sensor does not detect a heartbeat for a defined time window in order to provide early indication of possible cardiac standstill. This time window can be customised during the initial configuration. Based on the overall sensor measurements, another algorithm is also embedded to calculate the physiological welfare index, which outputs a colour code to refer to different conditions. For example, Red refers to high risk physiology whereas Green refers to normal condition.

6.2.3 Communication between the SEM and PC

The communication interface between the SEM and the PC is through Bluetooth with the SEM visible to any neighbouring Bluetooth devices. However, all devices are not able to collect data from the sensor since the connection is password protected and valid authentication is necessary to acquire the encrypted data from the SEM device. Equivital Manager is used to set the password for the SEM device, when connected through the USB cable, and it is not allowed to be done programmatically due to security reasons. Thus, the sensor data is sufficiently secured and privacy is ensured for the user of the SEM system.

The .NET SDK that is available with the Equivital system can be used to extract and display the sensor reading on a Windows based program. In this work, a dynamic link library (DLL) file is created using the SDK such that the variables are named accordingly and only the needed parameters and alerts are extracted from the sensor output. The created DLL is then used as a reference in the Telerehabilitation program and each of the parameter is called to be extracted as and when needed. However, for the connection of the SEM to the PC through Bluetooth, a Serial Port Profile (SPP) configuration must be used so that the program can extract the SEM data through a COM port, as shown in Fig. 6.3. SPP defines the protocols and procedures that shall be used by devices using Bluetooth for RS232 or similar serial cable emulation [148]. This is the only way that the PC is able to extract the SEM output as the manufacturers of the SEM device designed the SDK that way. Thus, it is important to ensure that the SEM can be connected through the outgoing COM port and the data communication occurs through it. It can be verified by using third party open source software like Tera Term [149]. Figure 6.4 shows the process of data extraction from the SEM to the Windows based application.

Once the Bluetooth SPP connection is established between the PC and SEM and the data transfer is verified, integration of the SEM system to the existing Telerehabilitation application can be done, as described in the in the next section in detail.

6.3 Integration of the Equivital System to the Telerehabilitation Application

As mentioned in earlier chapters, the Telerehabilitation application is designed and developed so that it can work smoothly even under low-bandwidth conditions. As such, it is important to note that the sensor data collected from the SEM should not be too large to congest the network and cause any disturbance in the consultation session. Since the physician would be interested in some of the fundamental physiological data from the patient, only those will

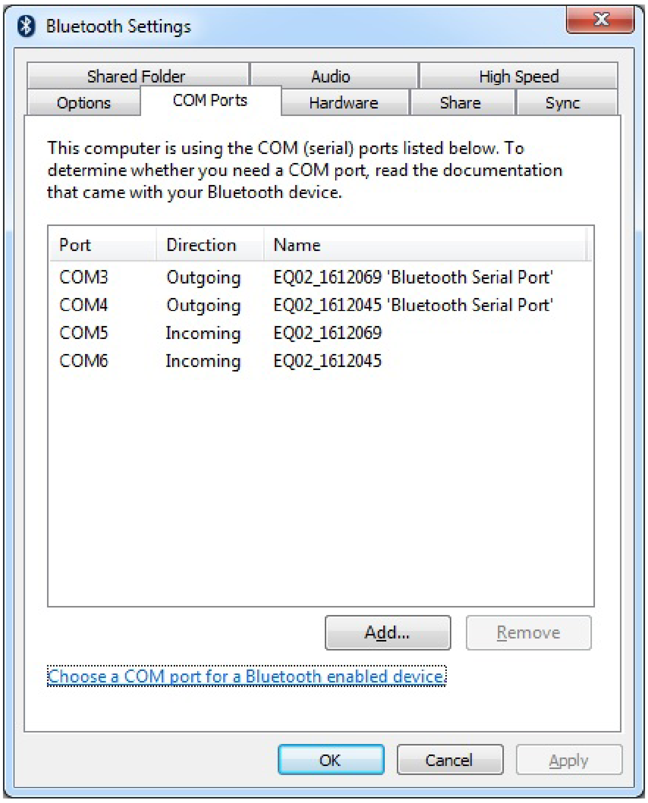


Figure 6.3: Example of Serial Port Profile when two Equivital SEMs were connected to the PC

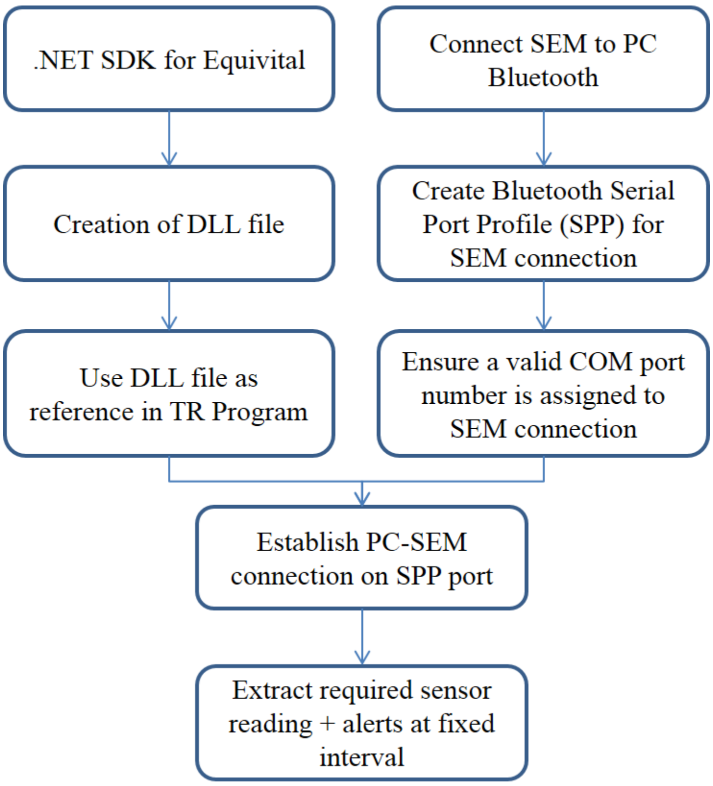


Figure 6.4: Usage of .NET SDK for SEM data extraction

be provided through the sensor even though it is capable to output continuous waveform data from the ECG and accelerometer sensors. The add-on part is thus designed such that only those derived data from the ECG, accelerometer and other sensors will be sent over to the physician rather than the entire raw data.

The COM port number is fed to the DLL file as a string parameter and once the correct COM port number is selected, the connection to SEM will be automatically completed. Depending on the frequency of the data collection (set at 5 second intervals by default), specified parameters will be sent from the SEM to the program. These selected vital signs are piggybacked on the chat message data that is sent from the patient to the doctor, with the sensor data being regularly sent even when the chat is not active. Appropriate delimiters are used and the data order is predefined such that it can be easily decrypted and presented at the doctor's end. The program can be modified to present the data in a graphical format or as a regular display of number and strings as and when it comes in. Figure 6.5 and Fig. 6.6 show the sample program screens with the Equivital SEM system integrated into the existing program at the patient's and doctors application windows respectively. At the patient's window, there is a checkbox to check and another box to specify the COM port number. Once the SEM is connected to the PC, the program can establish the connection immediately and extract the SEM output data and display the measured parameters in the program window to the right of the checkbox.

In the Doctor's window, the incoming parameters will be shown separately with corresponding labels after the message decryption. The data to be sent over

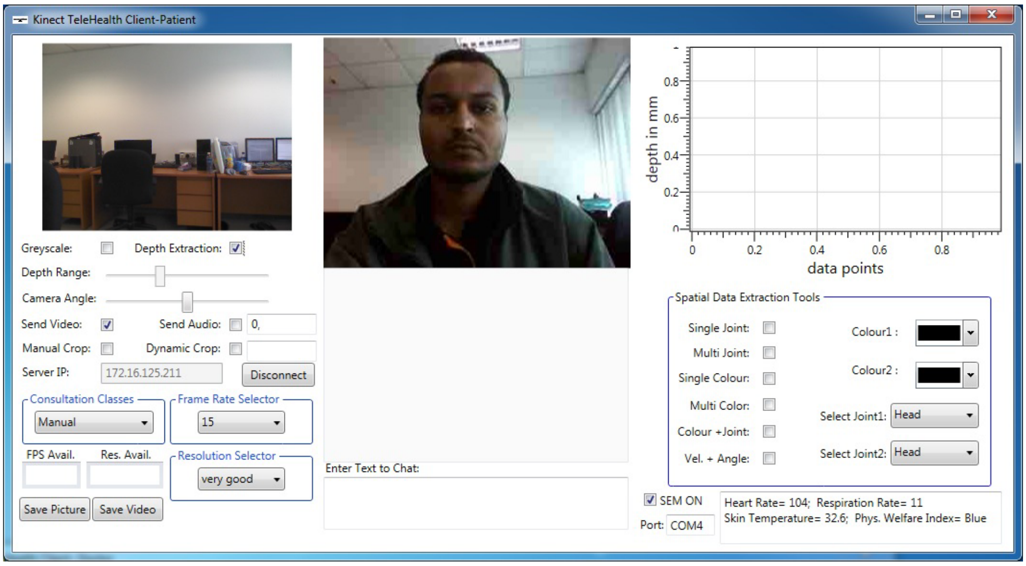


Figure 6.5: Patient's application window with the SEM checkbox in the bottom right

to the physician is limited to skin temperature, heart rate, respiration rate, and physiological welfare index calculated based on overall sensor outputs. There are healthy and cautionary ranges for each of these parameters [150] and the application is designed to indicate the status of each reading using a colour code in the doctor's window. For example, if the respiration rate is measured to be too high while performing the exercise, the window will display the reading with a red or yellow background colour depending on the reading from the sensor, as shown in Fig. 6.6. The function in this way would help the physician to consider altering the exercise routine when the existing one is detected to be having harmful impacts on the patient's physiology.

6.4 Equivital SEM Evaluation

Since many important clinical decisions are made based on the vital signs such as heart rate, respiration rate, and temperature, the accuracy of these mea-

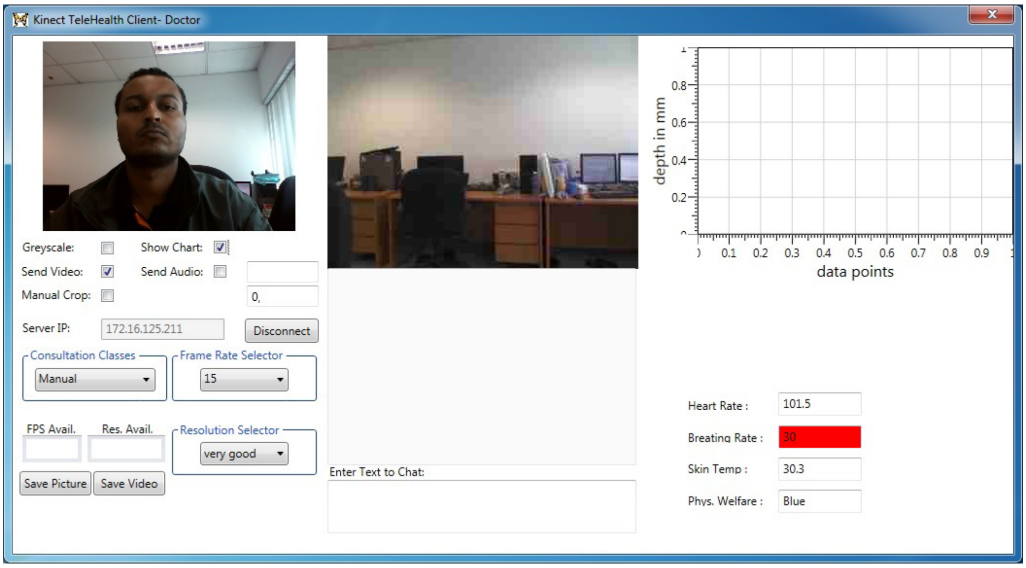


Figure 6.6: Doctor's application window displaying the incoming parameters

surements are essential. As mentioned earlier, these vital signs provide quantitative measures of the status of the cardiovascular/pulmonary system and reflect the function of internal organs and variations in these measurements are clear indications of change in the patient's physiological status. As such, accurate measurement of vital signs would assist the therapist in making clinical judgments so as to evaluate the progress and advise timely adjustments in the regular exercises in accordance with the patient's physical condition [76].

Evaluation of the Equivital SEM device has already been conducted by many research groups. This section will briefly explain the results from those past measurements as well as from the in-house measurements conducted as part of this work.

6.4.1 Available Results from Other Research Groups

The Equivital SEM system has been extensively evaluated by many researchers and organisations for testing its feasibility to their application requirements and the SEM device is already FDA certified to be used on human subjects [151]. This section will touch on the key findings from those studies as well as present the tests that are conducted to test the accuracy of some of the parameters/algorithms as part of this work.

Researchers led by Cuddy et al. at the U.S. Army Research Institute of Environmental Medicine (USARIEM) conducted extensive studies on the use of Equivital SEM device on monitoring the physiological status of a number of firefighters who were actively engaged in fighting fires in the western U.S. over a 3-day period [151]. The SEM device was used to collect, record, and display heart rate, respiratory rate, body position, and body temperature data from the firefighters while on duty. Their study revealed that the data collected using the SEM was exceedingly reliable for physiological monitoring and that the Equivital SEM system was easy to use and comfortable when worn by the users. Although the researchers did not do a comparison with other sensor modules, the sensor data seemed to be within the expected limits and the data trend were consistent in nature with the earlier data collected under similar settings of fire suppression exercises. Another recent study conducted by Tharion et al. for USRIEM focused on human factors evaluation of the Equivital SEM EQ-02 physiological status monitoring system [152]. The study focused on fit, comfort, utility, durability, and acceptability while wearing the Equivital system. The results showed positive results with high score in fit and around 90% score in acceptability. However the score was not so high for the affect wearing the belt have on their military performance. Since the setup in the Telerehabilitation application is going to be mostly in a controlled environment, it is acceptable in this case.

Liu et al. conducted a study on the validity and reliability of the Equivital SEM measurements during activities of various intensities among a group of healthy individuals [153]. On top of the usual SEM device, the team also made use of other external sensors which can communicate with the SEM; for e.g. the core pill for inner body temperature measurement and ancillary sensors for galvanic skin response and oxygen saturation. Statistical analysis was conducted to evaluate the reliability and validity of the SEM, with reliability measured based on consistency across multiple measurements on the same individuals and validity measured while comparing the measured value with the true value. Their results showed excellent conformity when compared to standard devices that are clinically accepted with a very low error of estimation, close to one correlation, and acceptable limits of agreement according to the Bland-Altman plots which is the most popular method of assessing the reliability and validity of biomedical devices [153]. Based on the results, the authors suggested that the system could be used extensively to study occupational health and other application fields which require physiological data monitoring.

Another study conducted by Van Wouwe et al. compared the sensor data from Equivital SEM with other two commonly used sensors [154]. The results showed that the accelerometer data from the Equivital model was as accurate as the other commonly used sensors and the cardio-respiratory data from the Equivital is better than the existing ones. In another instance, the Equivital SEM system with a modified belt design was used to continuously monitor animal physiological data by Liesel et al. [155]. The researchers used three different types of sensors on a captive wildebeest to monitor its heart rate and respiration rate. The Intraclass Correlation Coefficients calculated across the three methods showed good to excellent agreement between them throughout the 24 hour measurement duration and recommended the EQ02 system as a potential biometry device for similar purposes. From these above mentioned studies, it is clear that the accuracy and the usability of the SEM system have been extensively proven by various research groups and the sensors are even used in military training purposes. The next section will demonstrate the in-house tests that were conducted to gauge the reliability of some of the physiological parameters as well as embedded algorithms in the SEM device.

6.4.2 In-house Tests on Measurement Accuracy of the SEM Parameters

Some preliminary tests were done to evaluate the accuracy of the parameters measured as well as some of the algorithms embedded in the Equivital SEM system. As mentioned earlier, the SEM is able to measure skin temperature through the infrared thermistor embedded in the device. The skin temperature measurement was taken at different locations of the body, including forehead, arms, chest, etc., with two SEM devices and compared them with another set of measurements taken at those exact locations using a calibrated thermometer manufactured by Beurer [156]. The measurement results were analysed for the differences and the average standard deviation between the three sets of measurements were found to be 0.23°C. This is very insignificant difference considering the potential variability that would have been induced by the environment and measurement locations during the time of the test as well as the IR sensor variability of 0.3°C (Appendix A) and thus, these SEM measurement values are acceptable.

Once the belt is worn by the subject, the SEM device would be located on the left chest and thus the skin temperature reading will be taken at the same location. Studies have shown that the average skin temperature at the chest region measures around 32.3°C [157] [158]. As such, the warning limits at the doctor's program window are set accordingly, which differ from the limits in use for the average body temperature which measures at around 36.5°C [159].

In order to test the accuracy of the built-in algorithm of orientation detection and activity level, a volunteer subject was made to wear the Equivital belt with the SEM device connected. Different actions were carried out by the subject, such as walking, mild jogging, lying down face-up/face-down, and standing stationary. In all these activities, the algorithm was able to detect whether the subject was engaged in mild or intense activity levels and also able to detect the orientation of the patient whether it was upright, prone, side, or supine etc. with 100% accuracy. Another experiment was conducted to test the accuracy of the fall detection algorithm implemented in the SEM device which will send alarm signals once a free fall is sensed. Although these are not part of the requirement in the Telerehabilitation application, it would be useful for future developments if a continuous monitoring system for elderly/frail patients is to be designed using this sensor system. A few simulated fall scenarios were conducted and checked whether the sensor is able to detect the fall correctly and raise the alarm. In some scenarios the subject who was wearing the belt was asked to perform a sudden jump from a certain height and also do sudden drop to the chair while standing. In both these situations, the sensor correctly detected it as not a fall. Due to the difficulty in simulating a free fall, the belt was held at a certain height and dropped onto the ground. However, out of the 12 experiments conducted using two SEM devices, only on five instances, the sensor detected it as a fall resulting in an accuracy level of less than 50%; a much less than ideal value, probably affected due to the method used for the experiment. Although fall detection is not part of the current Telerehabilitation application, it is an area which needs improvement from Equivital. Since the sensor algorithm framework is constantly improved upon by the manufacturers, it is believed that the fall detection algorithm would be more accurate in the upcoming versions.

However, those parameters required for integrating with the current Telerehabilitation application are found to be reliable from tests conducted in-house as well as various other research groups and the Equivital SEM device is proven to be useful in this application.

6.4.3 Application Example Using the SEM Data in a Telerehabilitation Session

Prior studies have shown that there exists a linear relationship between the vital signs such as heart rate, respiration rate, etc. and the intensity of the exercise [76]. To understand the potential applicability of the add-on sensor module, a Telerehabilitation session is simulated here; first without using the SEM device data and then, with the SEM data. In this scenario, the physician remotely administers a Sit-to-Stand Test (SST) [135] performed by a patient through the Telerehabilitation application, whereby the patient is using the Kinect sensor at his end. In the first case, there are no SEM data available to the physician and

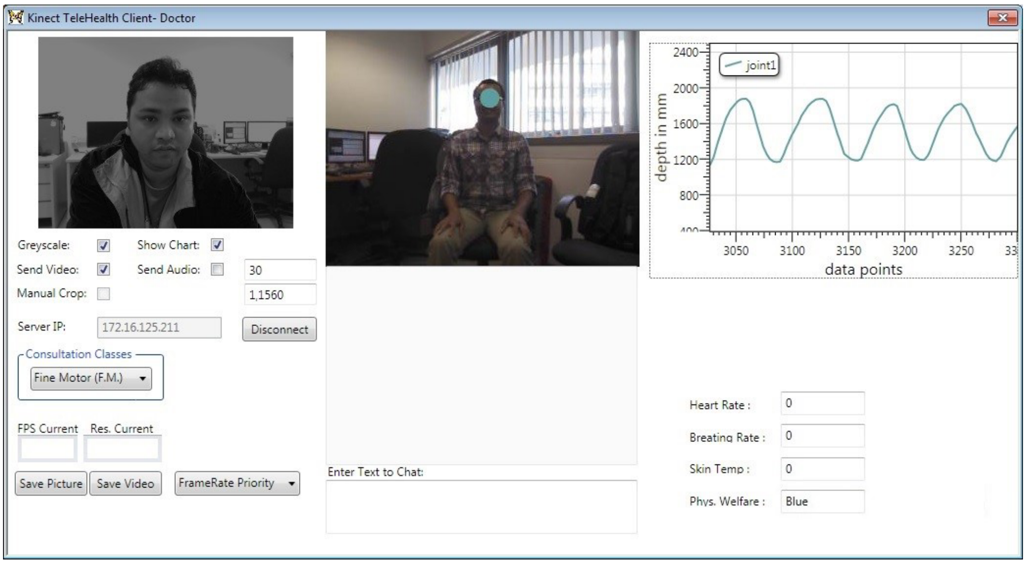


Figure 6.7: Sit-to-Stand Test being assessed by the physician using the Telerehabilitation platform without SEM data

his/her judgement is solely depending on the visual data from video streaming as well as the Kinect's depth tracking data, as shown in Fig. 6.7. Here, the physician has no insight on the patient's body response to the exercise intensity, which can be potentially inferred from the parameters such as breathing rate and heart rate.

However, when the same test (SST) is repeated on the same individual, but with the SEM device data, it is able to provide more information such as the heart rate and respiration rate which are good indicators of the fitness level of the person. Monitoring these data can also help the physician to gauge the recovery time, i.e. the time taken for these parameters to return to normal level, which can also be a good indicator of the patient's fitness level. Most importantly, if the Telerehabilitation software indicates an alarmingly high level of parameter reading from the patient, the physician can alter the therapy pattern to a less intensive one which may be safer for the particular individual. These parameters reading can also be included in the report generated on individual patients

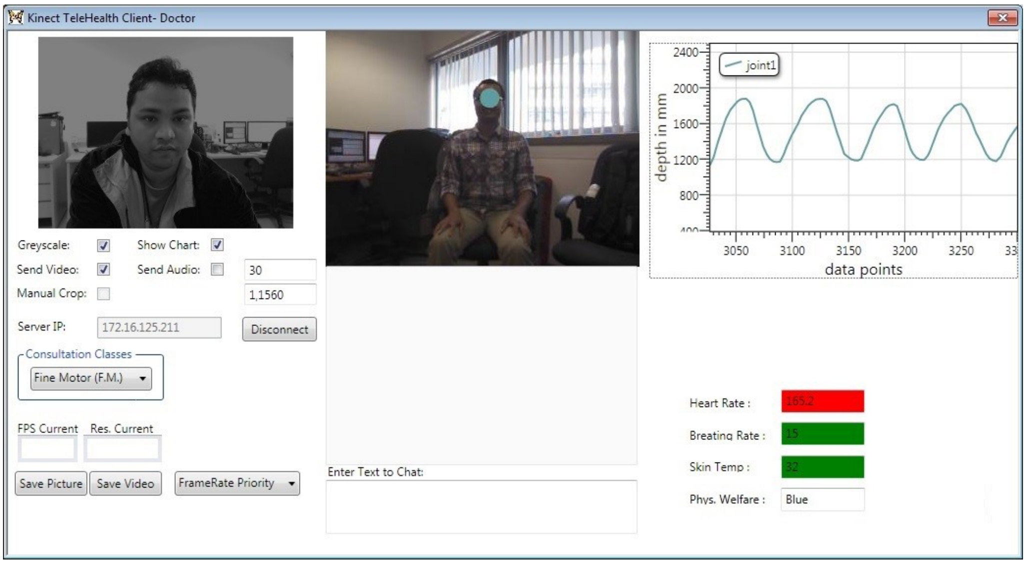


Figure 6.8: Sit-to-Stand Test being assessed by the physician using the Telerehabilitation platform with SEM data

as presented in Chapter 5. In this way, the physician also has the ability to monitor the patient's progress in terms of his physiological data together with other performance indicators presented in earlier chapters. Figure 6.8 shows the Telerehabilitation window at the physician's end while SST is being performed with the SEM data readings displayed on the right hand side.

6.5 Integration of Improved Telerehabilitation Framework into the Existing Platform

The framework for assessing the patient's progress as well as the data analysis part presented in Chapter 5 has been integrated into the original Telerehabilitation platform. This improved framework replaces the earlier version of Telerehabilitation tools presented in Chapter 3 and Chapter 4. The physician's client, as shown in Fig. 6.9, is able to select the joints to be tracked as well as the parameter to measure. It also includes the timer tools so that some of

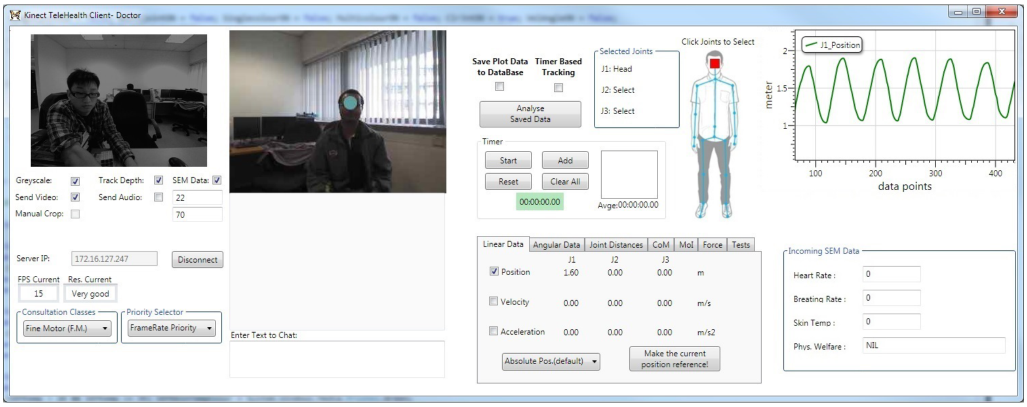


Figure 6.9: Integrated Telerehabilitaton platform for doctor's client

those timer based tests mentioned in Chapter 4 can be carried out remotely. The physician's client is also embedded with the option to enable the 'graphical display' and the 'save to database' function for the physiological data transmitted from the patient's end. The new integrated platform also includes the data analysis button which can be used by the physician to analyse and present the patient data as a report for easy diagnosis.

Similar modifications were made to the patient's client as well to suit the application requirements. As shown in Fig. 6.10, the patient's client includes an option to enable data measurement from the SEM as well as other basic functions as the user is not required to carry out any of the aforementioned tasks at his end. The window contains the graphical display of the depth information extracted using Kinect so that the user is aware of it. The new integrated system is more comprehensive that can be used in real world scenarios for TR applications in limited bandwidth settings.

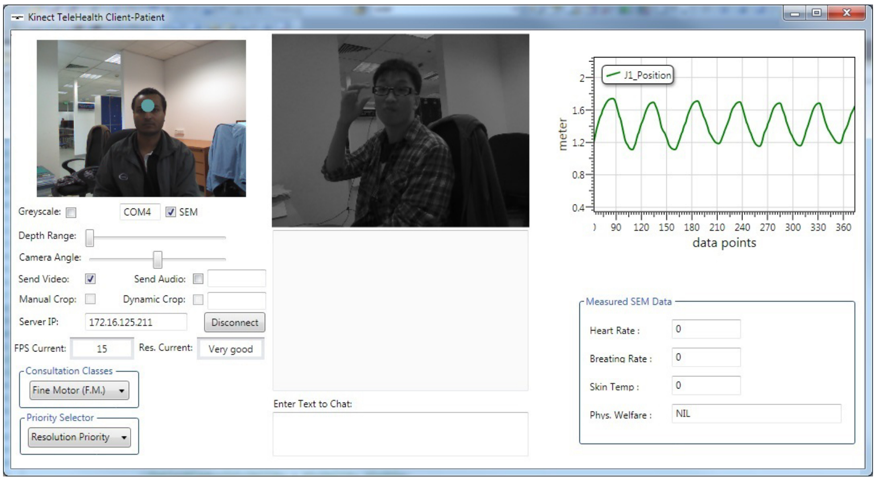


Figure 6.10: Integrated Telerehabilitaton platform for patient's client

6.6 Summary

Integration of a physiological monitoring sensor system from Equivital as well as the integration of the improved rehabilitation framework developed in Chapter 5 into the existing Telerehabilitation system are presented in this chapter. The readily available Equivital SEM device is able to measure various body parameters such as skin temperature, heart rate, respiration rate, etc. and it also contains embedded algorithms to detect body orientation, activity type, and alert the users on any potential measurement abnormalities after analysing the data from the built-in accelerometer, ECG, and other sensors that are included in the basic hardware setup. In addition to the SEM device, the system also includes a belt, which is an integral part of the solution. The sensor system has been integrated into the existing Telerehabilitation application and the user can connect to the SEM by specifying the COM port number and the data will be automatically streamed to the application using the Bluetooth Serial Port Profile configuration through the library file, specifically created for this purpose using the Equivital SDK. The sensor system has been widely tested by researchers for its accuracy and usefulness in similar situations and some preliminary tests on some of the measurement parameters and algorithms are conducted as part of this work as well. Although the free fall detection algorithm was found to be not very accurate right now, all other parameters which are useful for the current Telerehabilitation application are evaluated to be good. This addition as well as the integration of the improvements from the previous chapter to the developed Telerehabilitation system makes it a more comprehensive solution in terms of letting the physician monitor the vital signs of the patients in real-time while conducting the consultation sessions as well as providing the physician an option to analyse the measured data for easy diagnosis and to generate report for historical referencing.

Chapter 7

Conclusions

Rapidly ageing population poses grave challenge to countries like Singapore in terms of optimising their healthcare delivery system to the mass. As the percentage of the population in need of medical care rapidly increases, hospitals and other care providers in these countries are already finding it a challenge to cater their facilities to such high demand. Telemedicine, a method of delivering medical care by making use of information and communications technology advancements, is indeed the way forward. With the reach of Internet to almost all corners of the world today, it is a viable option to have which can help to curb the increasing medical expenses as well as assist in optimal utilisation of the limited available medical resources. Using Telemedicine also allows the population living rural settings to access specialised medical care, which is only available in the urban area, while accumulating substantial savings in terms of time, cost and effort of travelling to the hospital afar.

A lot of research has been conducted on the feasibility of having real time Telemedicine systems, especially for performing follow-up consultations of discharged patients and for the monitoring of such patients on a regular basis. As discussed in Chapter 1, Telemedicine systems were under development from as early as the 1960s. However, it was not until 1990s, with the advent of computer and Internet based telecommunication technologies, that Telemedicine research gained greater momentum and more advanced solutions were introduced afterwards. Following this trend, Telemedicine is also being used currently for other speciality clinical care applications such as dermatology, cardiology, oncology etc.

Another area that Telemedicine is being used is in the physical rehabilitation delivery. With the development of sophisticated optical and sensor based measurement, Telerehabilitation started to get increasing attention and it is evident from the research work conducted in this field in the past decade [34]. Multiple studies reported positive feedback from users, such as physicians/therapists and patients alike, on the acceptability of using Telerehabilitation for rehabilitation delivery and the satisfaction and comfort level in utilising such services were known to be very high [44] [45]. One interesting thing to note in these reports, however is that, the user satisfaction results were in correlation with the reliability of the communication link as well as smoothness of the Telemedicine sessions. That is, in these higher rated responses the communication channel was unaffected and the patients were able to experience a good quality consultation session with the therapists.

The above mentioned scenario is possible without any trouble under high bandwidth Internet settings. However, highly dynamic nature of the available network bandwidth makes it challenging to realise a reliable Telemedicine system which can ensure smooth consultation session across larger distances, especially so in developing countries where the Internet infrastructure is not well developed. As noted in earlier chapters, across the world, higher speed network connectivity comes at a premium, which is ill-afforded by the needy. According to the 2015 International Telecommunications Union (ITU) report [16], there are 3.2 billion Internet users around the world of which around 68% come from developing countries. However, the average network speed available to the people around the world is limited; even more so in the case of developing countries [17]. Thus, it is essential to design a Telemedicine system such that it is able to function smoothly even under constrained bandwidth environments, thereby enabling a meaningful consultation session between the physicians/therapists and the patients.

The work presented in this thesis focused on designing and developing a Telemedicine solution with specific emphasis on rehabilitation service delivery. The Telerehabilitation system presented here is equipped with the intelligence to adapt itself in accordance with the bandwidth fluctuations, enabling it to function well under low bandwidth settings. The system has embedded algorithms to measure and analyse the human body movements, captured using a Microsoft Kinect sensor, and to generate patient reports based on the analysis data. The system also included the option to add a readily available sensor that can be used for monitoring important physiological signals while the patient undergoes certain Telerehabilitation assessments. Experiments were conducted to validate the algorithms as well as other functions and the results proved the efficiency of the system as well as its capability to ensure its usefulness under limited network environments.

7.1 Main Contributions

In Chapter 2, design and formulation of a basic audio-visual communication platform was presented. The platform incorporated an algorithm to adapt the data rate, according to available network conditions by dynamically changing its resolution while maintaining the frame rate at a minimum level at all times. The platform made use of Microsoft's Kinect sensor to employ a dynamic cropping algorithm, which masks out unwanted portions of the frame while keeping only the human body information, thereby further reducing the data payload.

The platform presented in Chapter 2 formed the foundation to develop the Telemedicine solution further. In Chapter 3, a stand-alone framework for extracting depth information based on colour detection as well as Kinect's skeleton stream was presented. The method of sending 2D image together with the necessary depth information was presented as an alternative for high payload 3D video delivery under constrained bandwidth settings to enable the physician to have a good sense of spatial resolution in Telerehabilitation sessions. The chapter included experiments with multiple rehabilitation assessments to verify the usefulness of having such a framework.

Chapter 4 detailed the development of a Telerehabilitation system with designated consultation categories. The categories were tailor-made to suit remote physical rehabilitation delivery under low-bandwidth conditions while incorporating the necessary medical know-how on the minimum requirements for employing such a system in real-world settings. A new method of bandwidth adaptation was also implemented which was an improved version from the one introduced in Chapter 2 in terms of speed of adaptation, optimal utilisation of multiple parameters rather than the frame rate alone, as well as reduction in payload incurred by the already constrained network bandwidth. Experiments proved the benefits of having different consultation classes as well as the effectiveness of the new adaptation algorithm.

In Chapter 5, a much improved framework to carry out rehabilitation assessments using Kinect was presented. The framework, which was designed as a low-cost alternative for complex and expensive modern rehabilitation assessment tools that could be easily integrated into the developed Telerehabilitation system, included data extraction capability of human body joint motion in terms of linear and angular movements as well as an automated data analysis algorithm to quantify the measured data and present the results to the user in a report form. The new improved framework was tested to carry out some of the existing assessment methods in rehabilitation and the results showed strong correlation with the traditional methods and achieved near perfect assessment repeatability and reproducibility by minimizing the measurement errors.

As it became evident from the existing literature that, having the knowledge of essential physiological data such as heart rate, temperature, breath rate, etc. were critical in rehabilitation assessments, Chapter 6 introduced an option for the developed Telerehabilitation system to accept a third party physiological signal measurement sensor and to send the data over to the physician without overloading the available bandwidth. The improved framework developed in Chapter 5 was also incorporated into the system to complete the design of a comprehensive Telerehabilitation application which is ready to be deployed in the field for further trials.

The techniques formulated in this thesis can be used in other applications that require video streaming under constrained bandwidth conditions. Some of the preliminary works in this regard have been conducted and described in Appendix B at the end of this thesis. The section also contains details of a proof-of-concept study conducted regarding the design and development of a user interface for the Equivital SEM system using another programming platform.

7.2 Limitations and Suggestions for Future Work

Based on prior research as well as the experience acquired while working on this thesis, the following deserve further consideration and investigation in order to improve the Telerehabilitation system.

1. In the developed Telerehabilitation system, each individual client program executes the bandwidth adaptation function after getting feedback from the other end and it is not optimal, considering the fact that the client has to make the decision solely based on the other clients downloading bandwidth. It would make the system more responsive, if the server can be made more intelligent in terms of taking charge of bandwidth adaptation. With this, the server will be equipped with the capability to measure the data rate from the sending client and determine if any data is loss while the client uploads the data to the server, even before it forwards it to the receiving client. Once such a lost is noticed, the server can then immediately notify the sending client to adjust the data rate accordingly. Meanwhile the receiving client can still inform the server on the data rate it receives so that the server can forward the information to the sending client. This

additional step can ensure that both the uploading speed at the sender and the downloading speed at the receiver are taken into account while performing the bandwidth adaptations and make the adaptation process even quicker and improve the user experience, especially when both clients have very different bandwidths (i.e. when upstream bandwidth on one side is much different from the downstream bandwidth on the other side).

2. The rehabilitation framework makes use of the Kinect sensor's depth sensing and skeleton tracking capabilities to send spatial information over to the physician/therapist as a substitute for high payload 3D data, under low bandwidth settings. However, the Kinect has its own inherent limitations in terms of the accuracy of its depth data and skeleton tracking. As already pointed out earlier, Kinect is measured to be accurate to around 1mm at 1 metre distance and the accuracy level would drop to around 4 cm when the distance of the object tracked is 5 metres away from the sensor position [101]. Similarly, Kinect's stability of the body geometry varies when the orientation is changed; for example, the bone length may vary from 2cm to 5cm when the body is in frontal view and 45 degree view respectively [140]. Although these are acceptable for a low-cost sensor with such useful functionality, one has to bear in mind that the developed Telerehabilitation system is limited for applications that require greater accuracy.

   There are some works reported on making the Kinect data more accurate, using different techniques. One of these is done by Gao et al., in which the researchers used two Kinect sensors from different viewpoints and fusing the information to improve the accuracy of the Kinect motion data [160].

However the drawback is the long time (around 10 seconds) it takes to provide the data that makes it unusable in a live rehabilitation application, needless to say the additional cost of the second Kinect. Another interesting work by Valcik et al. tried to improve the accuracy of skeleton proportions estimated by the Kinect, by identifying different aspects influencing the skeletonisation (for e.g., direction of movement, phase of walk cycle etc.) and selecting the most reliable measurement from several sequences [161]. They reported reduction in the error in calculating bone lengths down to 1.7 cm, but the algorithm presented does not use live data from Kinect. This is one potential method to look at, certainly with improvements from the current algorithm, so that it can do the processing online, to suit a live Telerehabilitation scenario. Another work from Shu et al. tried using an extended Kalman filter for improving the Kinect skeleton joint tracking accuracy [162]. The technique also involved smoothing algorithms to stabilise the Kinect measurements and showed accuracy improvements. Again, there is no mention on the additional delay involved in the process and they only considered a fixed motion pattern for verification of the algorithm. Accuracy improvement is indeed an interesting area to focus on and to generate new methods to improve from the current settings.

On the other hand, the new version of Kinect sensor is advanced in terms of accuracy and stability of joint tracking, and a recent study done on comparing the accuracy between the two versions of Kinect confirms that [163]. The future versions of Kinect sensors are expected to improve further in this regard as well, enabling the developed system to be used in high accuracy applications.

3. Even though the Telerehabilitation system utilises an already existing third party sensor module for physiological data monitoring, it would be ideal if a cheaper module can be designed in-house for this purpose. The main disadvantage of the third party device is in terms of cost, as the Telerehabilitation system is also aimed for users from those developing countries. It would be greatly beneficial for them if such a device is available at a minimum cost, but still able to measure the fundamental physiological parameters such as body temperature, heart rate, breathing rate, etc. Another disadvantage of the current set-up is in terms of modularity, as the system solely depends on the Equivital sensor and the system has to be updated in terms of its library functions whenever the sensor manufacturers introduce a new model. This will introduce additional burden since it is essential to update the system in this case, in order to make the add-on functionality stay relevant. In addition, the Equivital SEM belt is worn on the patient's body and as such, there may be hygiene concerns if it is to be shared among multiple users. The high cost of the sensor may prevent individual users, especially those from the developing world, to be in possession of it and other alternatives are thus necessary.

   One potential consideration could be to make use of the low-cost sensor modules developed as part of the e-Guardian project by the team from National University of Singapore comprising of Assoc. Prof. Tan Kok Kiong and Dr. Yuan Jian [164]. In this work, the team developed a low-cost system that includes wearable devices which are capable of measuring blood pressure, monitoring heart rate, detecting accidental fall, etc. The e-Guardian adopts a modular design approach so that users have freedom to fit desired sensor modules to it. However, more work will be needed to adopt the sensor modules in the e-Guardian system to be used in the developed Telerehabilitation system and the main challenge in this case would be to establish a robust communication link between the two as the e-Guardian system uses a different communication network using ZigBee protocol [165]. Another potential candidate to fit in here is a contact-free microwave sensor to monitor vital signs such as heart rate and breathing rate developed by Lu et al. [166]. Although currently in the early stage of development, this low-cost device is one potential add-on to the TR platform, which may be a good solution for the multiple user challenge mentioned above.

4. The developed Telerehabilitation system is designed for Windows based computers as it is more widely used across the world according to this Gartner report [167] and also due to the fact that Kinect works best with Windows based operating systems [78]. According the same report by Gartner, as of 2013 statistics, smart devices such as smartphones and tablets based on the Android operating system are growing at a great rate whereas traditional PC and notebook market is declining. With this proliferation of smart devices in recent years, it would be useful to even larger community if the Telerehabilitation system is redesigned with an application focus on such devices. The basic communication framework

designed in this work with the data adaptation algorithms may be ported directly to another programming platform that is suited for smart devices to generate a mobile application for Telemedicine purpose. The challenge arises when spatial resolution is needed, which require a depth sensing device like Kinect to be used with the developed system. There are recent reports on a new version of Kinect's depth sensor to be used in smart devices to enable 3D sensing capabilities in these devices [168]. With the potential release of such add-on devices, it is indeed possible in the near future to have a comprehensive Telerehabilitation APP for smart devices with very similar functionality.

5. Another important area that needs further attention is the security and confidentiality of the transmitted data. The Telerehabilitation platform presented in the thesis uses default encryption for the audio-visual data while the depth data uses individual numerical codes for decryption at the receiver end. The Equivital SEM device communicates with the local PC using encrypted data as well and only the connected PC (through Bluetooth) will be able to view the actual physiological data of the patient. The transmitted SEM data from the patient to the physician uses numerical codes to be decrypted at the receiver end, similar to the case with the depth data. However, these are either the built-in encryption tools (default) or simple encryption methods, which may not be sufficient to defend a vicious attack from an external party. As such, it is essential to improve the current state. Going forward, the server, which facilitates the connection and communication between clients, can be made in charge

of the privacy as well through mechanisms such as encryption and user authentications. The connecting client could request for connection using a one-time token/ password to the server, which verifies and establishes connection only for that particular client. This one-time key mechanism may prevent other users from connecting to the server and tapping into the data without authentication [169]. The client-server set-up employed in the developed Telerehabilitation platform is made such that it facilitates such authorisation processes. Strict user controls are necessary in protecting the confidentiality of the data and as such, more user education may be needed to achieve this.

6. Thus far, the system has been tested under simulated network conditions whereby the available network bandwidth was constrained using software tools. Although the results of the tests were very good and they were helpful in validating all the implemented algorithms, it is essential to conduct trial runs under real world low bandwidth conditions such as those in the developing countries whereby a home based user and a distantly located hospital specialist is involved in a consultation session to truly understand the system performance. In the future, such an experiment is necessary to improve on possible shortcomings other than those mentioned above, so that the developed system can be ready for field deployment. Furthermore, while some of the Telerehabilitation assessment scenarios were simulated with a number of test subjects as presented in the thesis, the platform must be further tested by involving more medically qualified professional therapists so that the reliability and accuracy of the platform can be validated

and potential further improvement opportunities can be identified.

In conclusion, this thesis presented the design and development of a Telerehabilitation system that can be used satisfactorily even under constrained and highly fluctuating and unstable bandwidth conditions. It is important to have such a solution in the current situation, where the rapidly ageing population is a real concern and access to proper medical care is unevenly distributed with limited resource settings. This dissertation is a small step in enabling the communities to have access to such facilities and believed to be in the right direction for optimising the healthcare delivery system with innovative use of technology tools while making use of the existing infrastructure.

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Appendix A: EquiVital SEM Specifications

EQ02 LifeMonitor SEM Specifications

System Specifications		
Memory	8GB	50 days continuous monitoring[1]
Power	3.7V 300mAh Li-Po rechargeable cell	Recharge from flat in ~1 hour
Battery life	>24 hours[1]	
Communications	Class 1 Bluetooth 2.1	100m operating range[2]
Sensor belt	2 Lead ECG	
	Expansion derived respiration	
Connectivity	USB	2.0 compatible
Configuration	Via USB or OTA	Over the Air configuration from base updates
Physical Specifications		
Weight	38g	
Size	78mm x 53mm x 10mm	
IP Rating	IP67	Waterproof
Operating Temperature	-10 to +55°C	
Operating Humidity	0 to 95% RH Non-condensing	
Measurements		
Two Lead ECG	256 Hz	
Heart Rate	25-240 bpm	
R-R Interval	Derived	Short heart rate reporting window or long heart rate reporting window configurable
Breathing Rate	0-70 Breaths per minute	
Skin temperature	0°C to 60°C	±0.3°C Accuracy using IR Thermometer
Core Body Temperature		Wireless receiver compatible with Vitalsense accessories
Body Position	All orientations	Includes fall detection and motion
Physiological Welfare Index	Derived	
Tri-Axis Accelerometry	±2, ±4, ±8, ±16g	Configurable detection sampling rate 25Hz or 250Hz range[3]
Approvals		
	CE Certified	
	FDA Device Classification Class II	
	EU Device Classification Class IIb	
	Device safety EN60601-1 Classification	

[1] Subject to device configuration [2] Subject to environment [3] Release Feb 2012

Appendix B: Related Works

Potential Applications Using the Formulated Methods

This section details the related works conducted as part of the work presented in this thesis. The first section details the preliminary study in developing an educational enhancement platform by making use of the works conducted on the adaptive streaming algorithm. The section also discusses other potential applications using the techniques formulated in this work. The second section discusses a proof-of-concept work done regarding the usage of the Equivital SEM system and designing of a user interface in a different programming environment.

Realising an Education Platform- iLEAP, Using Adaptive Streaming Algorithms

Having students sit in hour (or more) long lectures while explaining complex theoretical concepts is the traditional way of teaching. We cannot expect all the students to understand these concepts by this method of teaching, since it can be really overwhelming for some to assimilate all the information at once. As such, it is highly recommended that, shorter lecture sessions are far more effective in enhancing the students understanding of the complex theories and their applicability.

A study conducted by Middendorf and Kalish [170] focused on the ebbs and flows of students focus during a typical class period. The authors determined that students needed a three- to five-minute period of settling down, which would be followed by 10 to 18 minutes of optimal focus. In another study conducted by Guo, Kim, and Rob [171] on the use of video lectures, it has been found that shorter lecture videos are far more engaging than the longer ones. They recommend the lecture videos be six minutes or less if possible to maximise the students understanding of the concept. Although these recommendations are not entirely practical to be implemented in face-to-face lectures, it can be realised by having recorded videos of the concepts taught in class and letting the student revisit whenever necessary. This type of lecture delivery also helps in making the learning process more flexible for students.

In order to realise a system which can be used to deliver video lectures to students, through the Internet, it is essential that it is able to function satisfactorily under differing network bandwidths. This is particularly important while considering the fact that, although the basic network infrastructure is present in countries like India and China, high speed Internet is still not available in many rural areas in these countries. Moreover, the majority of the world population (around 83%) resides in developing world [172] and as according to the latest statistics from International Telecommunication Union, 68% of the worlds total number of Internet users are from the developing countries, [16]. Thus, having the capability to function in network constrained environments is critical for successful implementation of such a solution.

Some initiatives were already taken place in the developing world to take advantage of the infrastructure development that followed the proliferation of the Internet based technologies. Desai and Shinde [173] discussed the use of E-learning in India, which makes use of Internet in education and the efforts of the government in letting the rural population climb the ladder of web based education. The authors conclude that although the government has initiated such activities, the universities should adapt their teaching approach to incorporate such technologies while making the education process more flexible. Another similar study by Chen et al. discusses the application of web-based education technology for the basic education in rural areas of China [174]. In this regard, these and other related studies indicate the importance of web based teaching platforms and their role in education system in countries all over the world. However, the challenge lies in successfully realising such platforms under low-bandwidth environments, which is common in developing countries.

This section explores the application possibility of employing adaptive streaming technologies in realising an integrated learning platform, iLEAP, in which the students will have an option for flexible viewing of theoretical concepts taught in class through shorter, bite-sized video chunks. The discussion focuses on the technologies that are already presented in the thesis for reducing the data size as well as for making optimal use of the limited bandwidth conditions. The platform, iLEAP, may also include a discussion forum for the students to have active discussions among themselves, overseen by the teaching assistants or the lecturers. Based on the topics raised in the discussion forum, the lecturer may select a few relevant questions and address them in separate videos and upload it on the learning platform, making the iLEAP platform very interactive as well as flexible to access, since the students have the flexibility of learning at their own time and space.

Implementation Guidelines

iLEAP is intended to provide a platform for students to make it easier to digest complex concepts in subjects by providing bite-sized chunks of information in a recorded video format that they can choose to watch and understand whenever they need, wherever they are, on whatever hardware platform, and as often as the students chooses to watch them.

There have been studies on the effectiveness for such kind of lecture delivery using new technology. A research conducted by Chris Evans [175], evaluated the efficiency of delivering revision lectures through audio-video contents as a revision exercise for students. The results suggested that students find podcasts to be efficient, effective, engaging and easily received learning tools for revision. Other studies by Baird and Fisher [176], and Edirisingha and Salmon [177] also provided similar results in the affirmative for using the technology in delivering lessons. Based on prior research by educators, it is verified that by delivering shorter lectures helps the students to focus on the concepts thoroughly and they are found to be more engaging than the longer ones. By implementing this application, it is expected to make the students learning process much more fruitful and flexible as it gives them the flexibility to catch up even if they miss the face-to-face lectures at times.

iLEAP can make use of the adaptive streaming technique for delivering the video content to the students device. Adaptive streaming technique works in such a way that, if the downlink network that the student is using is found to experience heavy traffic, the content quality (such as frame-rate or resolution) will be adjusted so as to ensure continuous streaming of the video. The algorithm for adaptive streaming has already been developed [178] as mentioned in Chapter 4 and the same mechanism can be made use of in this application as well.

The overall system may be developed to be accessible via a web browser so that any hardware platform with flash player installed shall have the ability to stream the video content as and when needed. The system would be employing a client-server architecture where the main hardware required would be a central server at the administrator side which will be used to store all the audiovisual contents and to host the discussion forum. The users, i.e. students, will be able to access this from devices which have a web browser installed with flash player support. Figure B.1 shows the rough framework of how the system architecture would look like upon implementation.

As presented in earlier chapters, priority streaming can be utilized in this case as well, based on whether the user is accessing lecture videos or laboratory experiment videos. Fame-rate or resolution priority can be implemented accordingly so that the user is able to stream in the videos without intermittent stoppages even when they are accessing the Internet from a low bandwidth environment. Colour to greyscale conversion can also be employed in situations when necessary as the experimental results have already shown that the data size can be reduced by around 43% by employing the technique [178].

Other Application Possibilities of Adaptive Streaming Algorithm

The bandwidth adaptation algorithm can potentially be used in many other applications where large size data transmission is key; for e.g. in video data

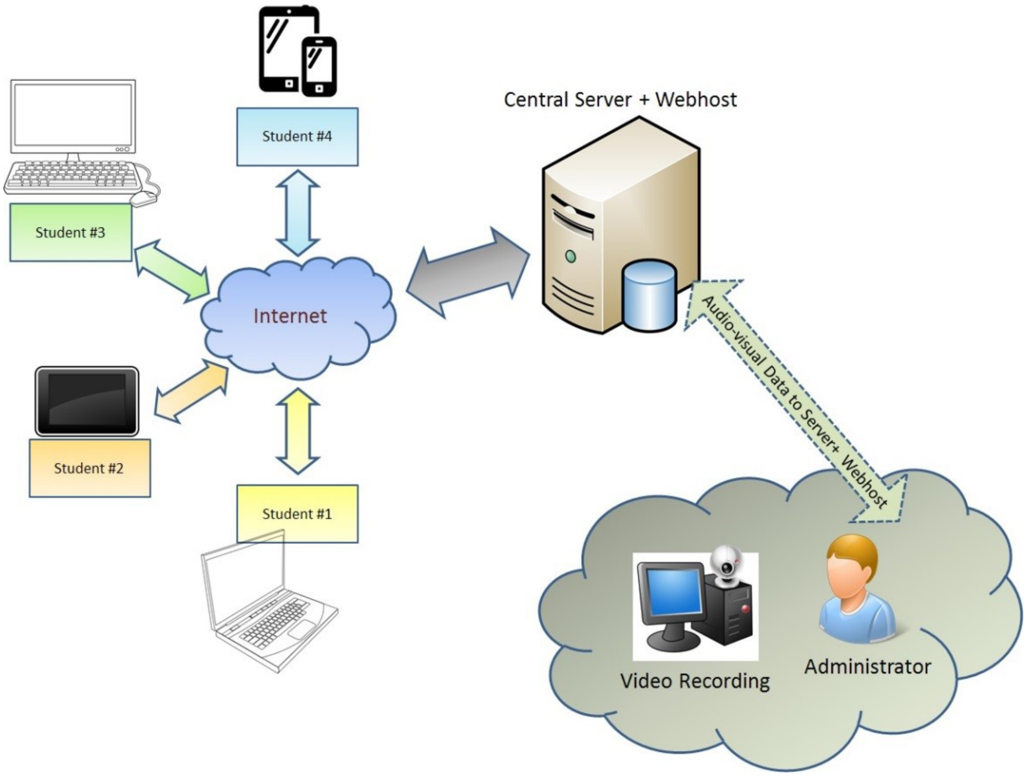

Figure B.1: iLEAP system architecture

transmission applications. One such instance is in remote driving of electric vehicles as elaborated by Kyaw et al. [179] where the adaptive streaming algorithm was used in last mile transportation. In this application, the solution is proposed to solve the last mile transportation problem to provide a cost-effective and sustainable door-to-door transportation using a shared fleet of vehicles which will be driven back to a common base by a remote driver, located in a central station, using audio-visual feedback transmitted from the vehicle.

In this application, the frame rate is always kept in a range between 10-15 while adjusting the compression parameter, or resolution, according to varying available network bandwidth. Thus, both frame-rate and resolution are adapted according to the situation so that the remote driver can safely manoeuvre the vehicle to the central station. Experimental results proved that the bandwidth adaptation algorithm was able to adapt the video data efficiently according to the dynamics of the wireless network and thus provided a safe solution for achieving acceptable performance in remote driving applications.

Another potential area that the adaptive streaming technology would be really useful is in road traffic monitoring. The security cameras that are in use for traffic monitoring have to stream video over to the control room continuously. It is often a challenge to keep the video without interruption due to the fluctuations in the available network bandwidth. The priority based adaptation algorithms can be made use of in this situation so as to ensure uninterrupted video stream at all time; possibly use resolution priority streaming in low-speed/ low visibility conditions and frame rate priority streaming in high speed conditions.

Proof-of-Concept Prototype of LabVIEW Interface for Equivital SEM Physiological Data

As presented in Chapter 6, the add-on sensor package using the Equivital EQ-02 sensor module was integrated to the originally developed Telerehabilitation application for observing live vital signs, including skin temperature, heart rate, respiration rate, and the overall physiological welfare index so that the physician can monitor these signals as the patient carries out different rehabilitation exercises during the consultation session. As mentioned in the same chapter, the sensor has also been extensively used in many other applications such as for monitoring the physiological data of firefighters and emergency workers while they are on duty as well as for monitoring the vital signs of soldiers while they are under training as an early detection/ prevention of any abnormalities.

There is a software, Equivital Professional, which displays the these data in a systematic way, by using graph plots and tables, so that the commander/ trainer can easily monitor multiple user data and quickly identify those with abnormalities and take necessary actions. However, the software comes at a hefty license fee which has to be renewed annually in order to continue using it. However, using the software development kit (SDK) from Equivital one can create a user interface which can potentially replace the Equivital Professional and display the user data with easy to analyse graphical plots and tables. This section explains further on using the aforementioned SDK to realise such a platform.

System Development

As mentioned in Chapter 6, the SDK from Equivital is .NET based and as such, .NET based programming languages would be one option to develop the data presentation application. However, data manipulations and presentation on graphical format can be very tricky using the Visual Studio tools such as C#. Considering this, National Instruments LabVIEW was chosen as the ideal platform for the system development in this case. LabVIEW software is used to build a wide range of applications in which other third party libraries can be integrated easily with a short development time needed to create applications with user friendly interfaces [180]. LabVIEW is a graphical programming interface with a number of built-in tools which can be used for effective data presentation. The dynamic link library (DLL) file which was created for the Equivital SEM device integration in the Telerehabilitation application is again utilized here. There are specific function nodes in LabVIEW to call the library file and other nodes to extract the parameters out from the SEM through the

DLL. As in Chapter 6, the connection between the PC and the SEM device will still be happening through the Bluetooth Serial Port Profile (SPP) configuration with a designated COM port being assigned for the data communication to take place.

There are two parts to the LabVIEW software, front panel and block diagram. All the user interface designs will be done on the front panel and the corresponding graphical programming will be done in the block diagram using a wide range of function blocks. The function blocks include common arithmetic functions, other specialized functions used in engineering such as different types of filtering, and also other functions to host external library files so that the user can make use of the parameters embedded in those libraries. LabVIEW is also capable of communicating with other devices as well through the Virtual Instrument Software Architecture (VISA) standard, which is used for configuring, programming, and troubleshooting instrumentation systems comprising GPIB, VXI, PXI, Serial, Ethernet, and/or USB interfaces [181]. A Windows compatible GSM/GPRS module with an embedded antenna, iTegno 38xx series, is connected to the communicating PC through USB to inform any concerned personnel through SMS in case any of the measured parameters is abnormal and the person (a firefighter, a soldier, or an athlete) needs urgent assistance [182]. LabVIEW can use VISA functions to communicate with this USB device through AT commands to either send or receive messages [183].

Two programmes were created for the SEM data presentation purpose; one for a single SEM and another one for multiple SEMs. The single SEM program displays all the parameters sent out from it with some of the parameters using a graphical plot on a separate page. This is used for testing the SEM devices individually for its overall functionality since this program displays all the parameters that the sensor module measures. Figure B.2 displays the front panel of the program page1 and the SMS alarm console can be found on the bottom right of the image. The user will have to specify the COM port number for the SEM and the GSM modules as well as the phone number to send the SMS alarm to. There is also an option to control the SMS interval so that the system doesnt send the message out repeatedly. Figure B.3 displays the page2 of the front panel, which includes the limit settings for the user to control so that the alarms will be triggered once the measurement is out of these limits. The page also includes sample graphical representation of some of the measured data.

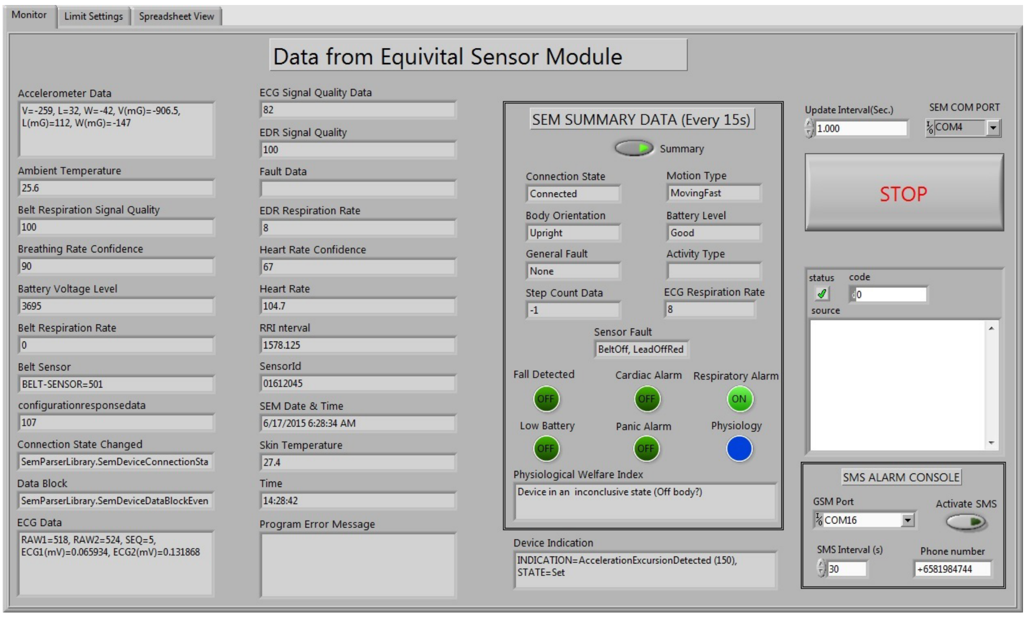

Figure B.2: Front panel page1 of single SEM program with output parameters and SMS console

Figure B.4 displays the page1 of the front panel for the multiple SEMs program. The page is designed to be in a table format with different SEM with

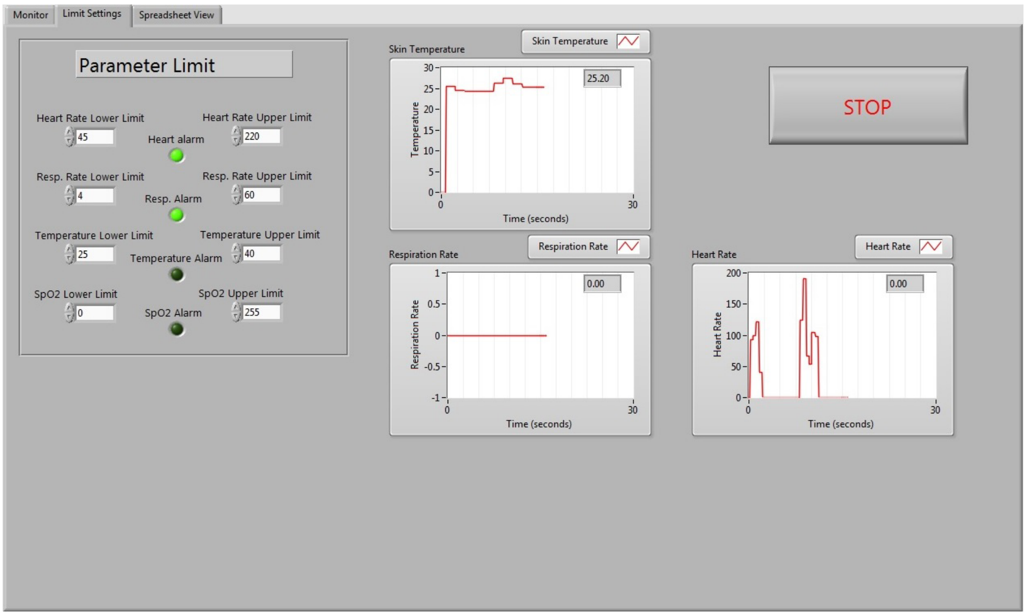

Figure B.3: Front panel page2 of single SEM program with the parameter limit settings and graphical data presentation

its unique sensor ID displaying individual measurements. For ease of analysing, only particular values are chosen to be displayed in the table. The program is also able to display the out of limit or abnormal parameter readings with colour code (red background) so that the user can easily see which sensor measured out of limit parameters and take necessary action immediately. The SMS console will again automatically send alarm signals to the designated phone number if any abnormality is detected. Figure B.5 displays the page2 of the program which is a graphical representation of the data from individual SEMs so that the user can see the trend in measurement history in case needed. The data can also be stored into the local hard disk in case necessary. The measurements displayed in the figures are simulated and as such, they may not represent the actual reading when the sensor belt is worn by a real person.

Moreover, since it is a proof-of-concept prototype, the program made for the multiple SEM measurement is created for a limited number of SEM devices (3 in this case), but it can be scaled up to more number of SEMs easily when necessary. One limitation though in scaling up would be the inherent constraint of the Bluetooth connections which limits the active connections to a single Bluetooth interface to a maximum of seven devices. However, this may be overcome by using multiple Bluetooth transceivers with each having its own SPP configurations to individual SEM devices.

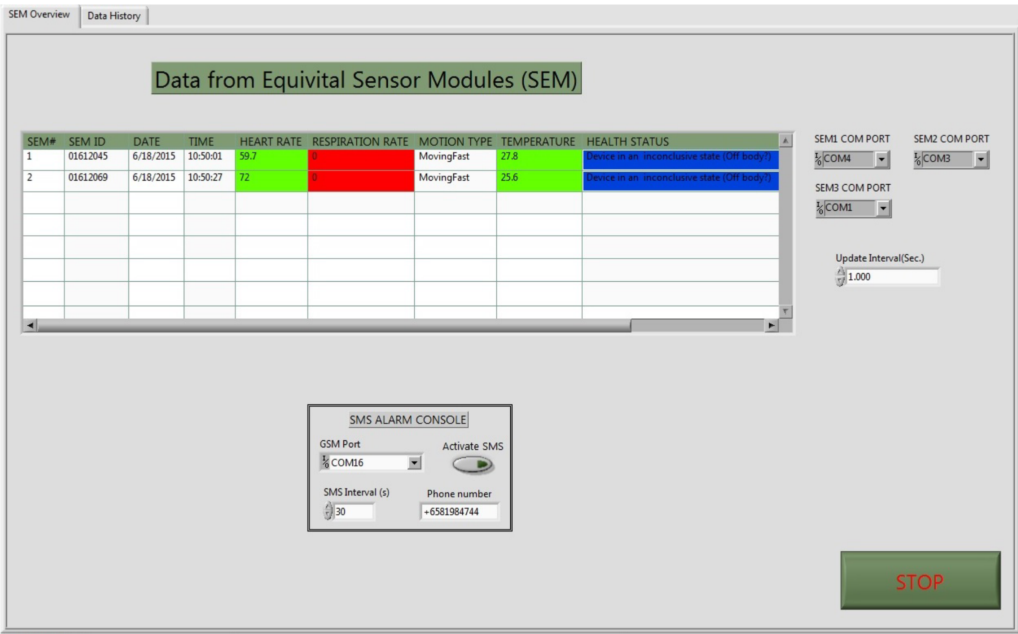

Figure B.4: Front panel of page1 of the Multiple SEM program displaying measured parameters in a colour coded table

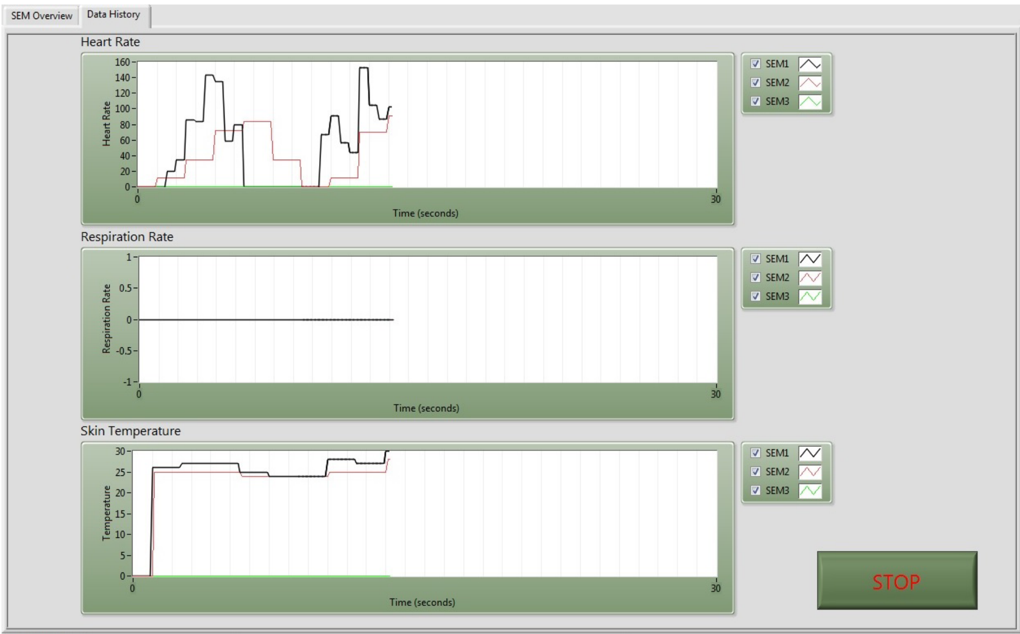

Figure B.5: Front panel of page2 of the Multiple SEM program with graphical presentation of measured data

Author's Publications

Journal Papers

Kiong, Tan Kok, Arun Shankar Narayanan, Helen M. Hoenig, and H. C. Koh, "Design and Development of a Kinect-Based Physical Rehabilitation System", *Submitted for publication.*

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