Nursing Robot Teleoperation via Motion Mapping Interfaces

by

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Abstract

Tele-nursing robots have great potential to support remote healthcare in contagious disease treatment, infection control and to provide in-home assistance to the elderly and disabled. Teleoperation interfaces must be intuitive and ergonomic, with low physical and cognitive workload to ensure an effective nurse-robot collaboration. Utilizing the motion-capture capabilities of a Virtual Reality (VR) system's handheld controllers provides a relatively cheap and intuitive means of controlling a robot. It can capture the human motion without the need for the expensive equipment a traditional motion capture system requires. Grasping and manipulating objects causes the most physical fatigue in the operator while teleoperating. The VR interface was thus designed to improve the user's ability to grasp and manipulate objects by improvising the motion mapping from the handheld VR controllers to the robot end-effectors. A pilot user-study (N=2) was conducted to compare the usability and performance of the VR interface with the Vicon motion capture interface developed for the TRINA, a mobile humanoid nursing robot. The results show a trend where the VR interface is faster in completing the tasks than the Vicon interface. A survey of the teleoperators also suggest that the users preferred the VR interface for teleoperating the TRINA robot. Motion mapping while great as an interface for large motions and free form teleoperation, suffers from lack of precision. The joystick which can generate small and discrete motion commands is capable of handling precise operations. VR controllers combines the intuitiveness of motion tracking and precision of the joystick through its own motion tracking capabilities and trackpad features, respectively. A variation of the VR interface with the trackpad controlling the end-effector motion of the Jaco arm was created. A

pilot user-study (N=2) was conducted to compare a gamepad interface, the VR interface without trackpad functionality and the VR interface with trackpad functionality. The operators teleoperate a Kinova Gen3 Jaco arm using all the three interfaces. The results suggest that the VR interface with the trackpad feature performs fastest for operations involving fine manipulation and the VR interface without the trackpad feature performs fastest for operations involving free form teleoperation. The user survey also favors the use of the VR interface to control the Jaco arm.

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Chapter 1

Introduction

1.1 Motivation

Tele-nursing can remove time and distance as barriers for the delivery of healthcare services [24]. Healthcare workers like nurses are often exposed to hazardous environments while tending to their patients and are vulnerable to diseases like Tuberculosis, measles, mumps, etc [25]. The the COVID-19 pandemic [26] or pandemic like outbreaks like the Zika virus outbreak [27], Yellow fever [28] and the Ebola virus outbreak [29] all bring to the forefront the need for qualified nursing personnel to meet the increased demand [30].

Robots can fit into this workflow in quarantine patient care and perform routine assistive tasks like cleaning patient rooms, delivering food and supplies, assisting patient motion, etc. Thus, robots can protect the healthcare workers from increased work times, stress, risk of infection and general discomfort. As robots allow the healthcare workers to not worry about their own personal safety, they can also focus on providing better emotional care to these patients and critical thinking to improve the quality of service provided to their patients [31, 32].

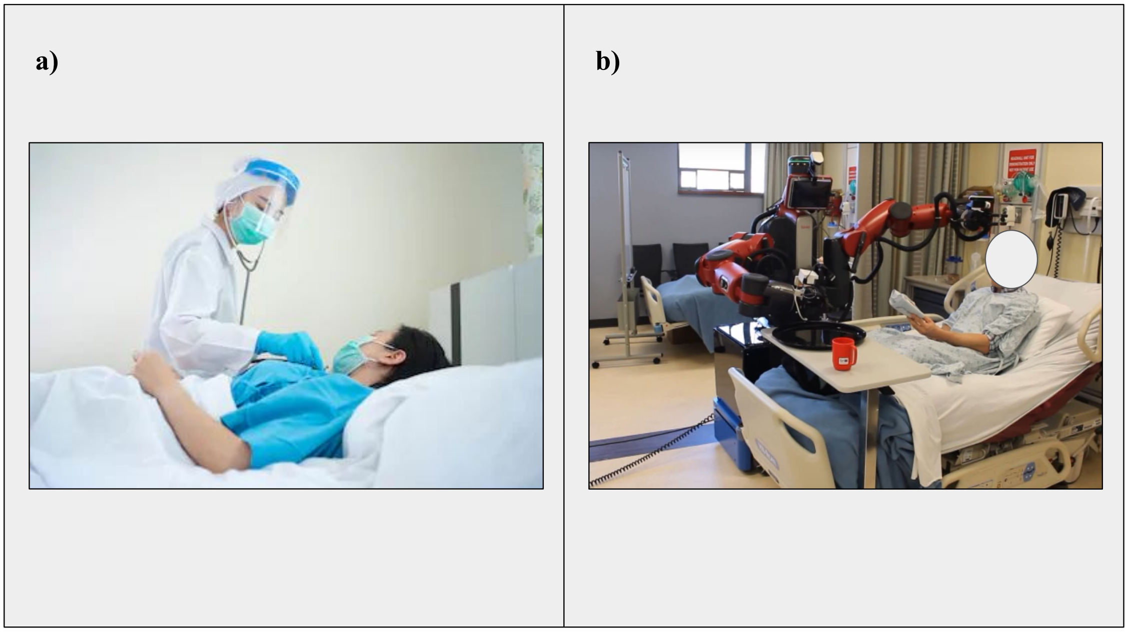

Figure 1.1: a) A nurse treating a patient in the quarantine ward. b) The TRINA robot tending to a patient in a simulation of a quarantine ward [3]

Due to various factors like work-related stress [33, 34], lack of job satisfaction [35] and aging society [36, 37, 38] there is an acute shortage of nursing workers [39]. This shortage also leads to certain areas having considerably lower number of qualified healthcare workers. In such situations timely aid might be impossible due to physical or temporal barriers.

Robotic Teleoperation is defined as operating a robot from a distance. Motion commands through a manipulator or joystick on the *Master* side is used to control the robot, often termed as the *Slave* [40]. Teleopration of robot agents provides the opportunity for nurses to control robots from a remote location to serve or monitor patients and perform their duties safely. With advancements in robotic and communication technology even remote places with no qualified healthcare workers will get access to timely healthcare thanks to the services of nurses from a different location. This also facilitates the delivery of specialized care for special situations, which otherwise might not have been possible. Remote or co-located operators team with robots through various interfaces. Robot control might be direct, supervisory with occasional intervention or shared control.

1.2 Limited Use of Motion Mapping in Teleoperation

The acceptance of these robot systems also depends on their usability [41]. There is an healthy attitude towards robotics in healthcare provided that they ensure safe practice and are reliable [42]. Having an easily usable robot will make the nurse's task easier and they won't perceive the handling of the robot as an additional chore but more like a way to accomplish their tasks. Thus, the robot interfaces for dealing with patients must require minimal training to become proficient in, allow nurses to perform tasks with minimal errors and should not impose an heavy workload on the operators that might cause physical injuries due to long term use [43]. High workload and learning effort of teleoperation interfaces can prevent daily usage of these robot interfaces and put up barriers in the nursing profession.

Recent developments in motion capture technology, particularly due to advancements in Virtual Reality technology means reliable human motion tracking has been at it's most accessible. The current state of teleoperation interfaces has had limited exploration into using motion mapping to control robots. Conventional motion capture techniques like Vicon Nexus are too expensive for most medical institutions and are limited in their portability. Other motion trackers like exoskeletons or exo-suits can limit mobility of the operator and might not be ergonomically ideal. As there has been limited exploration of developing teleoperation interfaces using motion capture technology, there is also limited explanation of proper design philosophies for a teleoperation interface, particularly for humanoid robots in nursing applications.

When the master (operator) and slave (robot) arms have a similar kinematic structure, through joint to joint mapping strategy the predictability of the slave arm configuration in response to the input from the master becomes intuitive [44, 45, 46]. As noted previously, using motions familiar to the user as a way to control the robot rather than using external hardware can make the teleoperation process easier [47, 48]. In summary, the optimal teleoepration interface should allow freeform control and provide maximum control to the operator while performing their duties [43].

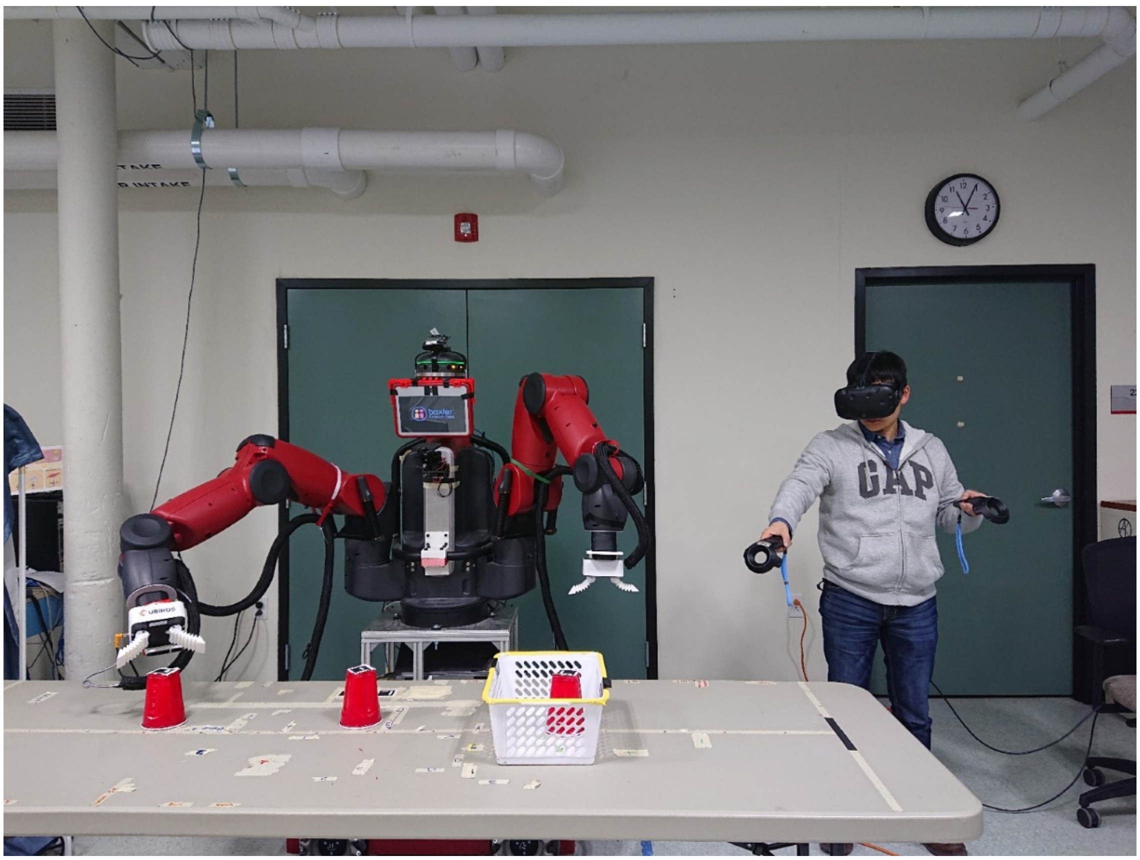

Figure 1.2: A teleoperator controlling the TRINA robot using the HTC Vive VR system. The operator is holding the two handheld controllers and wearing an head mounted display.

1.3 Motion Capture Technology in Virtual Reality Systems

As reported in Section 4.1, Motion Mapping thus can be a very intuitive way to control the robot. Based on experimental results comparing teleoperation interfaces (joystick controller, stylus device and motion capture) for the TRINA robot (Section 3.1), the teleoperation interface developed using motion capture was identified to be the easiest to learn and did not have a high operation workload. The participants for this experiment were the potential end users, namely nursing students. Motion mapping with Vicon is expensive and other alternatives which are more affordable need to be researched as this can result in the general acceptance of robot teleoperation in healthcare institutions. The motion capture technology offered by Virtual Reality systems through their handheld controllers can prove to be a feasible solution. The HTC Vive, a representative VR system that will be used to develop the teleoperation interface in this thesis, has 24 infrared sensors in it's controller ring that is tracked by two lighthouses. The Vive system is accurate within fractions of a millimeter with very low latency [49, 50, 51]. Therefore more research into developing and testing feasible teloperation cheaper interfaces for robots for nursing applications using these VR controllers is required to address the growing need for safe and reliable robotic technology in healthcare.

In this thesis, a teleoperation interface for a mobile humanoid robot and a robotic arm using the VR motion trackers is proposed and validated. The interface is designed to be as intuitive, efficient and ergonomic (in terms of physical workload) as possible to make it appealing to the potential end users, namely the healthcare workers. From the experimental results mentioned in Section 4.2, manipulation was identified to be the most fatiguing and complicated task as picking up objects requires considerable motion coordination and can become tiring if not well designed. Thus, if the manipulation of objects are intuitive and easy to learn through teleoperation, the interface itself becomes viable.

1.4 Virtual Reality Controllers as a Teloperation Interface

Feature	Vicon	HTC Vive
1.Motion Tracking Technology	Optical markers captured by IR cameras attached to the human body	IR sensors on the Handheld controllers tracked by IR radiation from motion tracking lighthouses
2.Accuracy [50]	76 μm	0.242 mm
3.Information extracted	Joint angles of the subject's human skeleton (limbs) which gives end-effector translation and rotation	End-effector translation and rotation, x and y coordinates of human finger location on controller trackpad, four buttons that can be used for input
4.Bi-directional communication	Requires additional hardware to be built and attached to subject's body	Haptic feedback in the form of vibration of controllers is possible

Table 1.1: Overview of the salient features of the Vicon Nexus and HTC Vive systems from the perspective of building a teleoepration interface

Using the Vive controller for motion tracking offers many benefits. The system is cheap, portable and the motion accuracy is sufficient enough for nursing tasks. The entire system is easy to setup and calibrate. The Kinematics of human arm is different from robot arm kinematics as the robot arm is designed to avoid singularities. As a result, using motion mapping like Vicon is contrained by human kinematics. However, the

Vive interface is designed to let the operator feel like they are holding the robot gripper as a tool and guiding it to perform various motions and tasks. In this way grasping motions can be easily executed. The two controllers while allowing freeform control also has buttons that can be used for various distinct robot controls, something not provided by other motion capture techniques. The joystick interface allows for much better control of robots than motion tracking when it comes to performing small motions or very delicate operations. The user is able to provide discrete commands for small motion, something that is difficult to provide with conventional motion tracking [52]. In the interface developed for the Kinova Gen3 arm (refer Section 3.2), the operator can use the trackpad available on the VR controller to adjust the robot end-effector and perform the fine motions required to execute delicate tasks like picking up small objects. In this way the VR controller lets the designer take advantage of the benefits of both motion tracking and joystick-like inputs to develop an intuitive and accurate interface to control robots.

In order to highlight the effectiveness of the Vive interface and it's comparability to the Vicon interface, which is identified as the best interface for free-form teleoperation (refer Section 4.1), a pilot user study on the TRINA robot was conducted. This study involved tasks that highlight skills commonly required for performing nursing tasks like arm-hand coordination for object grasping, bi-manual coordination for perception camera control and loco-manipulation for navigating in a cluttered workspace. This study found out that the Vive interface could perform all the tasks that the Vicon interface was able to perform at a comparable task completion time.

The Vive interface also provides a blend of motion capture capabilities with the option of providing discrete commands through the buttons and trackpads. This allows the user to perform tasks that involve free-form teleoperation that motion mapping is successful at and also precise manipulation that joystick based interfaces excel at. A pilot user study on the Kinova Gen3 Jaco arm was conducted using three interfaces: gamepad, Vive and Vive with trackpad functionality that lets the user control the end-effector. The results from the study show that the use of the trackpad to teleoeprate fine movements of the end-effector in combination with the free-form motion capabilities of the motion capture of the Vive system is comparable to the gamepad interface.

In this thesis we provide the design of the first use of VR controllers to control a mobile humanoid robot built for use in an healthcare environment. The design methodology provides a detailed summary of the factors considered while developing the teleoperation interface for nursing robots using motion capture. We detail how the characteristics of a VR controller, which is a combination of motion tracking and a joystick will, help us develop an interface that is ideal for nursing tasks. The interface design and motion mapping choices were dictated by the needs of the tasks and the robot's capabilities. The developed interface was evaluated using pilot user studies that compare it against contemporary teleoperation interfaces, namely Vicon and Joystick controller.

1.5 Thesis Outline

The duties of an healthcare worker and the current state of the art technology of robots in healthcare will be expanded upon in **Chapter 2**. The different ways in which teleoperation interfaces have been developed is also surveyed and reported with special emphasis on interfaces that use motion capture technology.

In **Chapter 4**, the lessons learned based on our experiences of evaluating teleoperation interfaces that use gamepads, stylus based devices and motion capture through a series of experiments is reported. This section will illustrate how motion capture technology is an easy to use and intuitive form of teleoperation control input.

After introducing the robot platforms used for teleoperation in **Chapter 3**, the design methodology and the implementation of the teleoperation interfaces is presented in **Chapter 5**. The motion capture interface utilizing the Virtual Reality controllers is implemented on a mobile dual-armed humanoid robot, TRINA and a 7 degree-of-freedom robotic arm, Kinova's Gen 3 Jaco arm. The design and control layout of these interfaces is detailed in **Chapter 6** and **Chapter 7** respectively.

The results of a pilot user study is reported in **Chapter 8**. User studies of the interface for both the TRINA and Jaco robots are compared with other contemporary interfaces like the marker based motion capture system (VICON) in the case of the TRINA robot and a joystick controller in the case of the Gen3 arm.

The plans for further user studies, possibly with healthcare workers teleoperating the VR interface will be discussed in **Chapter 9**. Finally, the potential future work that can enable robot teleoperation like enhanced visual perception through active telepresence, augmented reality, bi-directional communication through haptic feedback and the use of the Head Mounted Display of the VR system is also detailed in **Chapter 9**.

Chapter 2

Related Work

2.1 Interfaces for Tele-nursing Robots

2.1.1 Robots in Healthcare

The Ebola virus [53, 54], the Zika virus [55, 56] and the COVID-19 pandemic crisis [57, 58], highlight how dangerous it can be for an healthcare worker who has to care for their patients in an highly infectious environment. Currently robots are used in various fields in medicine, ranging from surgery [59, 60, 61, 62, 63, 64, 65] to rehabilitation [66, 67, 68, 69]. Surgical robots are designed for performing extremely precise operations and their required range of motion is limited as large range of motion is unnecessary. Current nursing robots are mostly limited to providing remote monitoring and counseling. This means most of the commercial robots are mobile telepresence robots like the RP-VITA [7] (refer Fig. 2.1 d)). [70, 71] have all developed low-cost alternatives to the RP-VITA complete with video call capabilities. Such robots have found application in places from old-age homes [72, 70, 73, 74, 75] to neo-natal intensive care units [76, 77, 78].

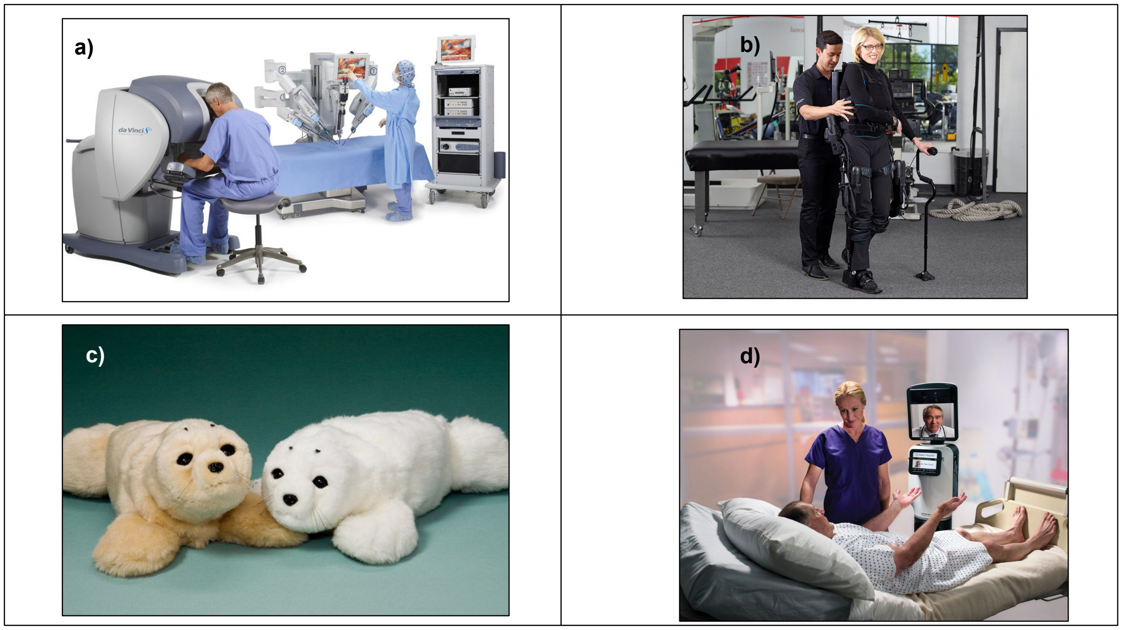

Figure 2.1: Representative robots in healthcare: a) The da Vinci robot with the surgeon's console in the foreground and the surgical robot in the background [4] b) The EksoNR exoskeleton used in stroke rehabilation [5] c) Paro robot is often used in therapy for patients suffering from dementia by providing an outlet for companionship [6] d) The RP-VITA robot used in telemedicine for counseling and monitoring [7]

2.1.2 Nursing Tasks

However, a nursing worker's tasks go beyond just providing counseling and monitoring. Their tasks involve Food preparation and serving, moving items like the medical cart, barcode scanning, taking measurements like body temperature and handling the associated equipments, moving the patients, cleaning, etc (refer Table 2.1 [3] and Table 2.2 [22]).

Task	Sub-Tasks	Actions
1. Food Preparation	Placing objects on Tray	Pick and place beverage cup
		Pick and place food containers
		Medicine utensils
	Inserting straw into cup	Pick up straw
		Insert straw
2. Serving	Move tray from cart to table	Grasp tray
		Lift tray
		Move food tray from cart to table
		Put down tray
	Move objects from tray to table	Pick and place beverage cup
		Pick and place food containers
		Medicine utensils
	Move tray with weight from cart to table	Grasp tray
		Lift tray
		Move tray
		Place tray
	Handover to patient in bed	Place Beverage cup
		Place food containers
		Place Medicine cup
3. Moving	Push Medical Cart	Grasp handle
		Push
	Patient transfer bed	Grasp handle
		Push
	Portable computer station	Grasp handle
		Push
	Walker	Grasp handle
		Push
4. Collecting	Collect medical supplies into a container	Pick and place syringes
		Pick and place suction tube bags
		Pick and place IV tube bags
5. Operating Cabinet	Open and Close cabiet drawer	Grasp handle to open
		Push drawer to close

Task	Sub-Tasks	Actions
6. Barcode Scanning	Scan Barcode on gauze bag	Pick up scanner
		Scan
	Scan Barcode on patient wrist	Pick up scanner
		Scan
7. Taking Measurement	Dip humidity sensor to liquid container	Dip sensor
	Take blood oxygen saturation	Rach to patient
	Hand over wireless blood pressure cuff	Grasp cuff
		Handover cuff
	Temperature - remote scanner	Center scanner light and read
	Temperate- contact scanner	Rub across forehead
8. Supply Preparation	Take sterilized supplies out of bag	Peel big syringe flush bag
		Peel small syringe flush bag
		Peel syring needle bag
		Peel gauze bag
		Tear flush bag
9. Medical Device / System Operation	Syringe operation	Peel open bag
		Fill a flush
		Dispose used syringe into container
	IV operation	Take off old IV bag
		Unplug old IV tubes
		Plug in IV tube into IV bag
		Turn roller on IV tube
		Hang new IV bag on IV stand
	Suction system operation	Unplug tubes from old container
		Take suction container off
		Set new suction container
		Plug in draining tube to new container
10. Moving Patient	Lift patient arm	Grasp patient arm
		Lift patient arm
11. Cleaning	Remove dirty linen	
	Remove patient room debris	
	Move urinals, etc	

Table 2.1: List of tasks performed by nurses, the actions to be performed and sub-tasks associated with these tasks [3]. These are some of the tasks expected to be performed by nursing robots that address patient care.

In addition to these tasks a nurse is also often required to interact with patients and provide emotional care if needed. Thus nurses must be able to respond to a patients requests and complaints in a compassionate and appropriate manner [79]. The nurses must also be able to make decisions in response to any abnormal occurrences in a timely and correct fashion.

Task	Comms	Mobility	Measurement	Manipulation (C/F/VF)	Tool use
Tele-medicine Intake / consultation Patient rounds	Y	 N Y	Y		
Unskilled physical tasks Turn off alarms Move equipment carts Food / meds / supply transport Feeding by mouth		Y		C	
Cleaning Discard soiled linens Clean bodily fluids Disinfect surfaces Change bedpans		Y		F	Y
Diagnostics Nose / throat swabbing Stethoscope placement Attaching vital sign monitors	Y	Y	Y	F	Y
Interventions, non-invasive Feeding via nasogastric tube Intravenous (IV) and arterial line manipulation Draw blood samples from lines Drainage and Foley catheter container measure and change Manual bag ventilation		Y	Y	F	Y
Interventions, invasive Intubation IV insertion Catheterization Injection Lab draws		Y	Y	VF	Y

Table 2.2: Mapping nursing tasks a nurse is expected to do in the times of COVID-19 pandemic to primary functions [22]. CF/VF indicate coarse/fine/very fine manipulation. Y and N stand for Yes and No respectively.

2.1.3 Robotics in the Nursing Workflow

In order for nursing robots (refer Fig. 2.2 and Table 2.3 for a collection of nursing robots and their capabilities) to be accepted into the general healthcare workflow, they need to be capable of accomplishing or aiding the execution of the tasks mentioned in Section 2.1.2. Healthcare robots have to be designed to support nurses and healthcare workers while enhancing healthcare [80]. Robots must be capable of enabling easy and efficient execution of repetitive tasks and nurses are central to the integration of such technology into healthcare [81]. Nursing robots should be reliable, shouldn't be

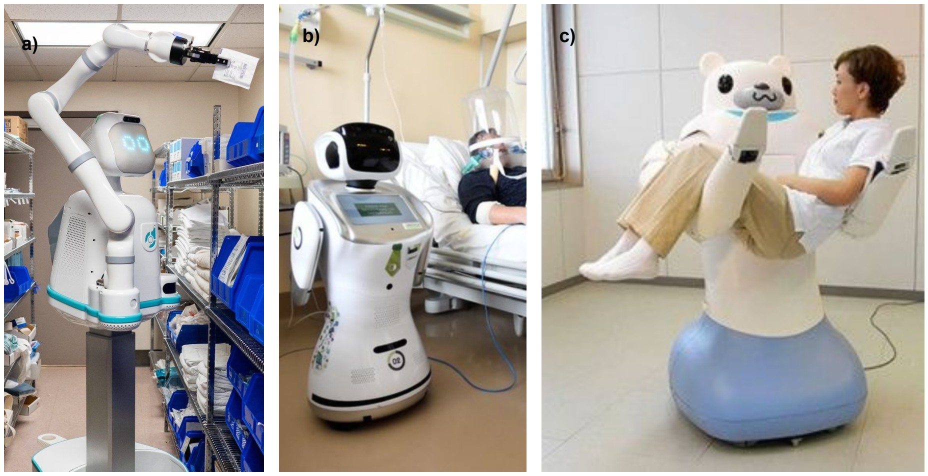

Figure 2.2: Represetative Nursing Robots: a) The Moxi robot [8] b) The Tommy Robot [9] c) The RIBA robot [10]

dehumanizing and also have intelligence similar to human capabilities [82, 83, 84]. A multi-purpose nursing robot should be capable of aiding patient mobility, monitoring and feeding when the physical presence of an healthcare worker is not possible [85].

Robot Platform	Robot Role
RoNA [86]	Nursing Assistant. Locomotion and lifting patients for patient transfer
TRINA [3]	Humanoid Nursing Assistant. Locomotion, material handling and manipulation and telepresence
OSU Ebolabot [87]	Nursing Assistant. Locomotion, material handling and manipulation
UVD [88]	Mobile autonomous robot, disinfect environment using mounted ultraviolet lights
Moxi [8]	Autonomous mobile robot, material delivery
PARO [89]	Emotional companion. Responds and react to gestures like patting, touching, etc (refer Fig. 2.1 c)).

Table 2.3: Representative nursing robot platforms and their roles.

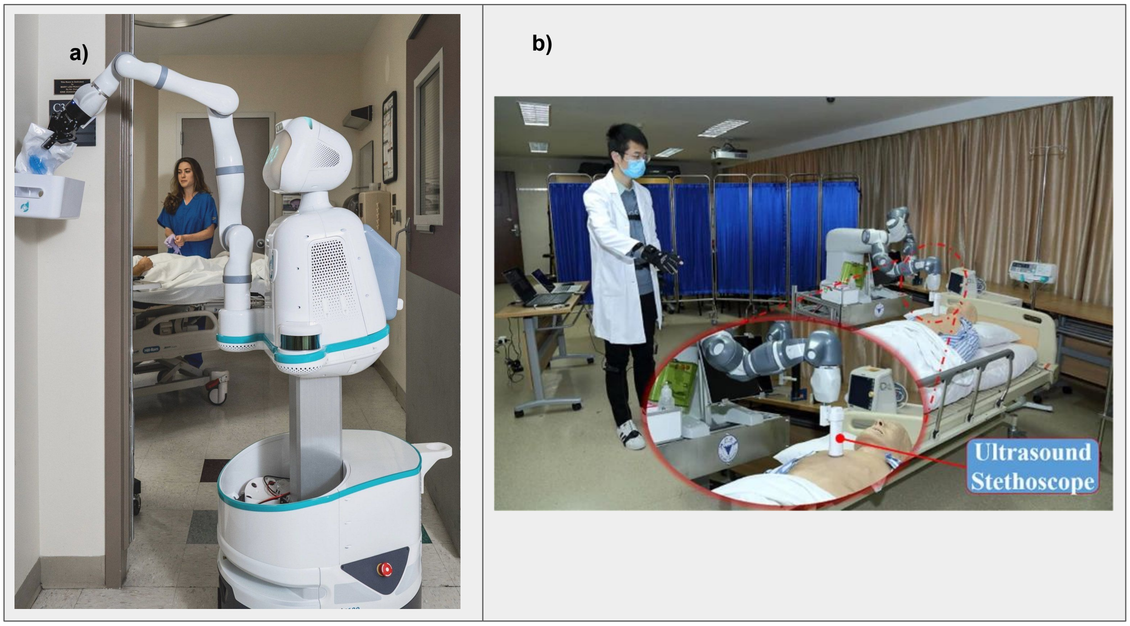

Figure 2.3: a) The Moxi robot autonomously functions and performs delivery of medicines and food using it's mobile base and it's robotic arm [11]. An healthcare worker can work simultaneously to monitor the patients vitals and perform any other necessary procedures. b) An healthcare practitioner teleoperates an ultrasound stethoscope mounted on a robotic arm using a data glove that. The hand motion detected by the data glove is used to control the robotic arm and stethoscope. The operator is close to the robot and the patient but the entire procedure remains contactless ensuring the workers safety [12]

The robot can be in the same environment as the healthcare worker and they can be performing separate tasks or can be collaborative or they could be in different locations and the nurse can be a supervisor or an operator of the robot (refer Fig. 2.4). When the robot and the nurse are close to each other, they are said to be co-located and the robots can be termed as proximate robots [90]. When the robots and patients are co-located, the robot can be autonomous (refer Fig. 2.3 a)) or teleoperated (refer Fig. 2.3 b)). A single operator teleoperating multiple robots can also provide the opportunity to improve efficiency and negate shortage of qualified healtcare workers. For example, a single therapist can simultaneously control three rehabilitation robots to treat three upper limb stroke rehabilitation patients through teleoepration and telepresence [91].

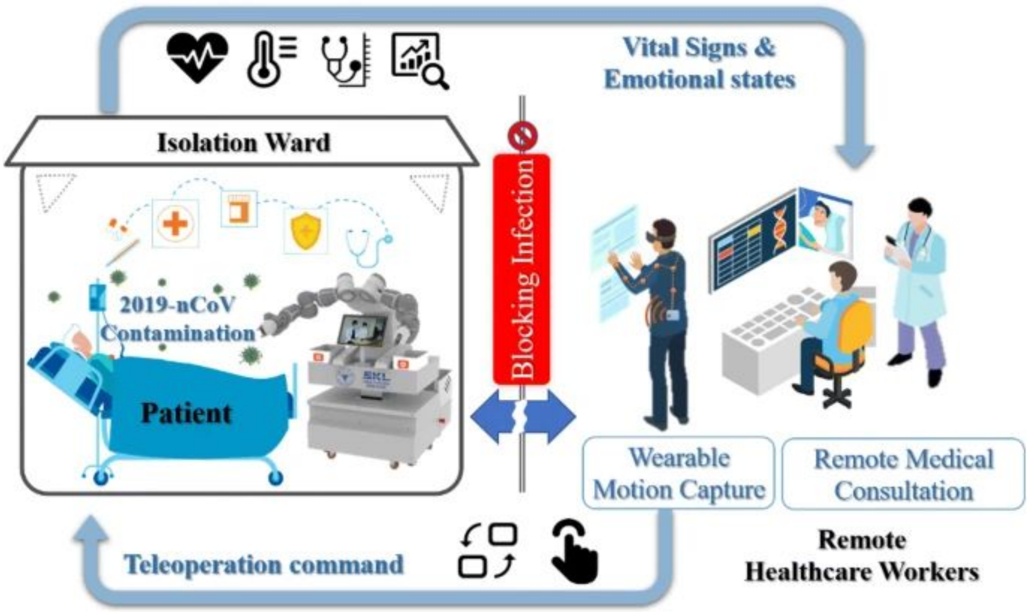

Figure 2.4: Framework for a motion capture teleoeperation interface used to teleoperate a mobile dual armed robot to care for a patient infected by the 2019-nCoV virus [12]. The operators teleoperate the robot, monitor and communicate with the patient remotely away from the isolation ward, thereby ensuring the operator is protected from infection.

2.1.4 Nursing Shortages

Nurses suffer from increased workload due to an inadequate supply of nurses [92, 93, 94, 95] resulting in reduced staffing, increased overtime [96] and increased loss of life or occurrences of avoidable deaths [95]. This shortage in nurses will be further magnified by pandemic conditions which will be more taxing on the existing medical system [97, 98]. The nature of work in nursing healthcare poses risks of physical problems for the nurses [99, 100, 101, 102].

In addition to affecting the physical health of the worker the mental health is also negatively affected due to the worker being overworked [98, 103, 99, 104]. Factors like job stress and emotional burnout could lead to a large turnover of nurses further compounding the nurse shortage problem [105, 106].

A robot in nursing must serve as an extension of the nursing worker, allowing them to perform their duties even when they are incapable of being physically present to provide aid due to temporal or physical barriers. For example, rural communities have chronically suffered from a lack of adequate health resources. The limited number of licensed practitioners and the large distances from adequate healthcare has severely affected the quality of healthcare in such locations [107, 108]. However, the presence of telemedicine robots can improve the quality of healthcare in such locations [109]. There is a need to generate robotic technology with greater mobility and communication capabilities to support the healthcare workforce for the future in quarantine, hospitals and nursing facilities [110].

2.1.5 Teleoperation Interfaces for Nursing Robots

Robot platform	Capability	Autonomy	Interfaces
Mobile telepresence [7, 111, 112, 113, 70, 71, 72, 70, 73, 41, 75, 114]	A/C/N	Self-navigation Obstacle avoidance Human-following	Touchpad, joystick, GUI
Mobile manipulator [3, 115, 8, 116, 117, 118]	A/C/N/M	Self-navigation. Pick and Place	Gamepad, stylus, GUI, touchpad, motion capture system, Interaction with a replica
Humanoid [119, 120]	A/C/N/M	NA	Exoskeleton, Virtual Reality, Stylus devices

Table 2.4: An overview of commercial and prototype tele-nursing robots, with their Patient Assessment (A), Communication (C), Navigation (N) and Manipulation (M) capabilities.

Developing an intuitive and easy to use interface is vital for making the teleoperated robot more acceptable for wide-scale use by nurses in actual applications. As will be expanded upon in Section 4.1, using human motion mapping as a teleoperation interface will lead to an interface which requires less learning effort and and is intuitive to use.

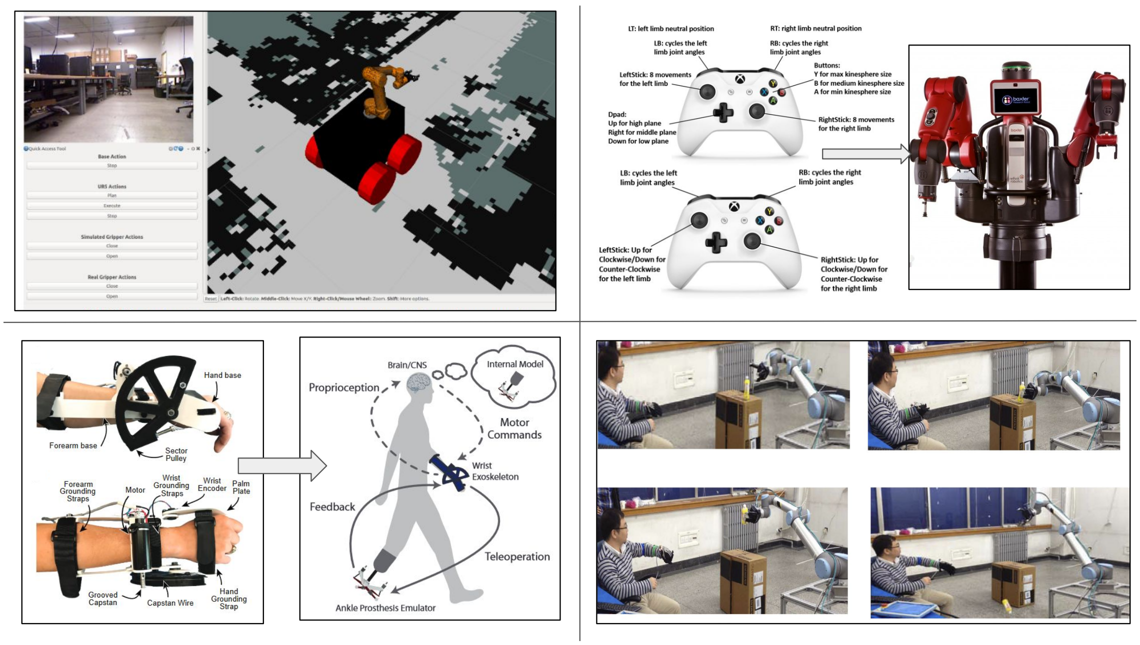

Figure 2.5: Going through the different reperesentative interfaces clockwise from top left: A simple GUI interface to teleoperate a mobile manipulator [13]; a gamepad interface developed to teleoperate the Baxter robot [14]; a data glove to teleoperate a robotic arm [15]; an hand based exoskelton whose motion is used to control an ankle prosthesis [16]

2.2 Teleoperation via Motion Mapping

Human motion can be tracked to teleoperate robots in a multitude of ways. Exoskeletons [121, 122, 123, 124, 125], Markerless motion tracking [126, 127, 128, 129, 130, 131], Markers or IMU based motion tracking [132, 1, 133, 134], commercial virtual reality and gaming controllers [135, 136, 137, 138] and data gloves [139, 140] have all been used to impart human motion to teleoperate robots for various applications.

Input interface	Controlled motion
Human motions	
Customized cockpits	Whole-body [141]
VR controller	Multiple hand configuration [137]
	Whole-body [142]
Exosuit	Balancing [143]
	Manipulation and positioning [144]
RGB-D camera	Whole-body [145]
	Bi-manual manipulation [146]
Marker-based	Whole-body [1]
IMU-based	Whole-body [147]

Table 2.5: Representative interfaces for online control of humanoid robot motion coordination.

However, these motion capture methods are not without their demerits. Highly precise motion capture methods like the Vicon systems and Xsens IMU systems are expensive [148, 149, 150]. Motion capture systems like Vicon are infeasible in most environements because of the logistics involved with the large amount of hardware required for the system to operate. The price and the requirement for a large dedicated space for the system might make it too expensive of an investment for most healthcare institutions. Cheap depth camera systems like the Kinect provide the enticing possibility of enabling cheap teleoperation interfaces. However, the depth detection systems are not always accurate and can result in dire consequences during teleoperation [151]. Exoskeleton systems also might not be compatible for every user and can also restrict the natural motion of most users while teleoperation making extended operation times uncomfortable.

2.2.1 The Case for Virtual Reality controllers

With the development in Virtual Reality technology in recent times, using the motion trackers of these systems as a means to teleoperate the robot is promising. The Vive

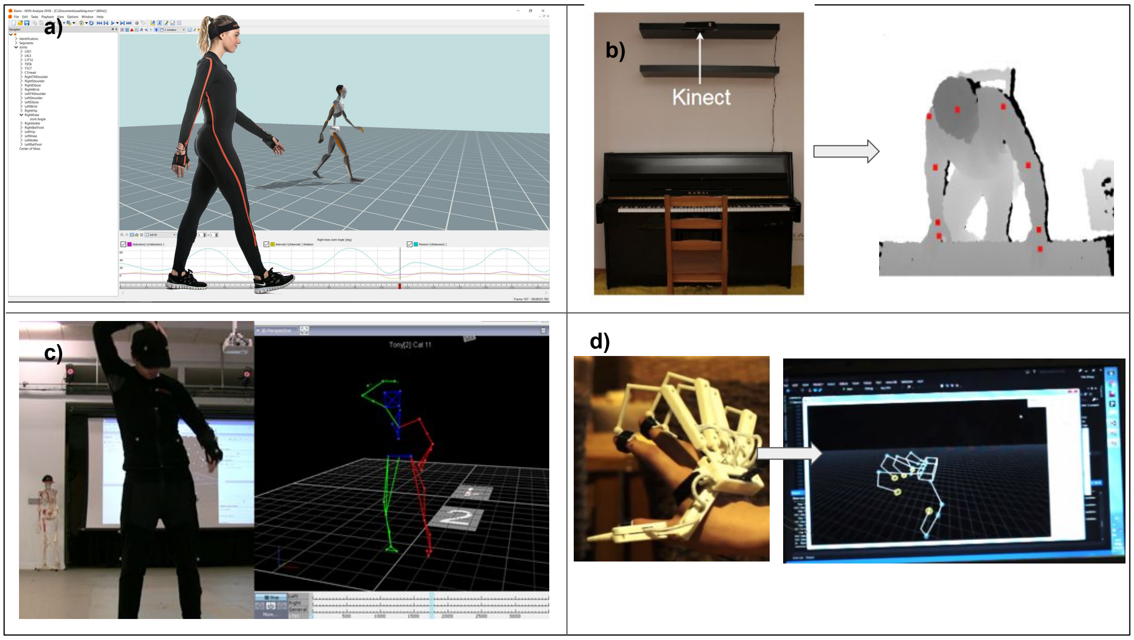

Figure 2.6: a) Motion capture using the XSENS MVN IMU based motion capture suit [17]; b) Motion of a pianist captured using a Kinect RGB-D camera [18]; c) Motion capture of a human using IR optical markers, IR Cameras and the Vicon Nexus system [19]; d) Motion of an hand captured using a flexible exoskeleton [20].

is a representative commercial Virtual Reality system released by HTC and consists of two handheld controllers with buttons, a Head Mounted Display and two lighthouse trackers that track the handheld controllers (refer Fig. 1.2) [152]. In addition to the buttons the controller also has a trackpad which also doubles up as a button. Research has started exploring the use of using the motion capture capabilities of these VR systems [153, 154, 155].

However, in literature there is a lack of interfaces utilizing the versatile nature of VR controllers and using them to control mobile humanoid robots. VR controllers exhibit accurate motion capture capabilities, are made up of buttons and trackpads that give an added dimension of information extraction that is absent in conventional motion capture techniques and are cheap and portable. Thus, this piece of technology can facilitate the development of easy to use and versatile teleoperation interfaces capable

Motion Capture Device	Precision	Ease of Operation	Ergonomics	Portability	Potential for Haptic Feedback	Cost
Marker Based (Vicon Nexus)	Good	Bad	Good	Bad	Bad	Bad
IMU Based (Xsens MVN)	Good	Good	Neutral	Good	Bad	Bad
RGB-D camera (Microsoft Kinect)	Bad	Good	Good	Good	Bad	Good
Exosuits or Exoskeletons	Good	Neutral	Bad	Neutral	Good	Neutral
VR controllers (HTC Vive)	Good	Good	Good	Good	Good	Good

Legend: Good — Neutral — Bad

Table 2.6: An evaluation of common motion capture devices based on: a) Precision: Accuracy with which an object of interest can be followed; b) Ease of Operation: The difficulty in setting up the motion capture system like system calibration, etc; c) Ergonomics: The physical comfort level associated with using this motion capture system; d) Portability: Space required for the system, components required for operation, etc; e) Potential for Haptic Feedback: If the hardware allows for potential haptic feedback for a bi-directional communication enabled interface f) Cost: The cost of all the components

of controlling highly complex robot systems like humanoid robots or mobile manipulators. There is also a lack of literature that focuses on expanding upon the motion mapping strategy from the controller side to the robot that is designed for ease of teleoperation for healthcare workers. This thesis will provide a detailed description of how the benefits of utilizing motion capture through VR controllers can be used to teleoperate a mobile humanoid robot and a robotic arm through an intuitive and efficient interface.

Chapter 3

Robot Platforms

3.1 Tele-Robotic Intelligent Nursing Assistant (TRINA)

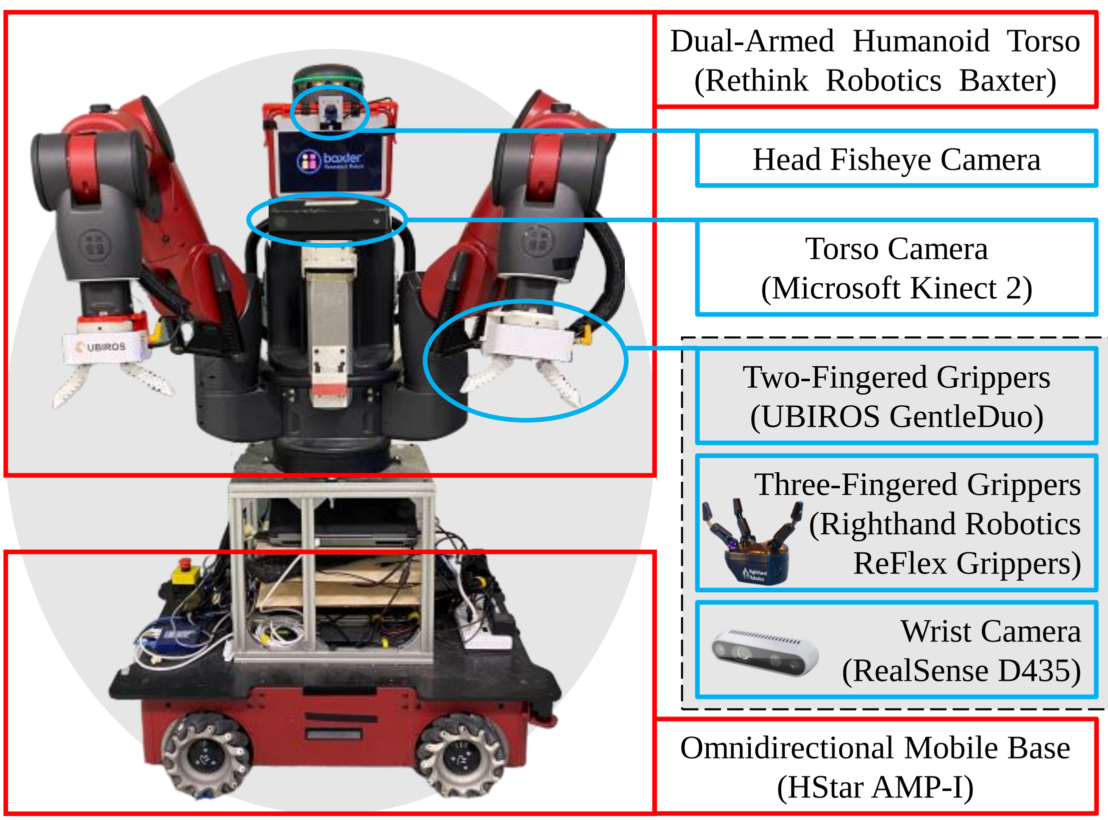

Figure 3.1: Tele-robotic Intelligent Nursing Assistant (TRINA) system.

As seen in Fig. 3.1, the Tele-Robotic Intelligent Nursing Assistant (TRINA), consists of a dual-armed humanoid torso (Rethink Robotics Baxter), an omnidirectional mobile base (HStar AMP-I) and a pair of two-finger soft grippers (UBIROS GentleDuo) or a pair of three-finger grippers (Righthand Robotics ReFlex Grippers). The visual sensor suite of this nursing robot includes a 180° fisheye camera attached to the robot head and two Intel RealSense D435 cameras mounted on the two wrists. There are provisions on the robot torso to attach camera sensors like a Kinect, a Realsense camera or a regular webcam for object detection and location.

The Baxter humanoid robot has 2 seven degrees of freedom arms whose individual joints can be actuated and controlled to move to desired orientations and positions. The two handheld controllers from the VR systems are used to control the two arms of the robot and the base is moved using the trackpad (full controller configuration is detailed in **Chapter 5**).

3.2 Kinova Gen3

Figure 3.2: The Kinova Gen3 robot arm equipped with the 2f-85 Robotiq gripper [21].

The Kinova Gen3 (refer Fig. 3.2) is a 7 Degree-of-Freedom ultralight, power efficient, portable robot arm boasting a maximum payload capability of 4 kilograms. The robot is equipped with a 2f-85 Robotiq gripper that has a maximum grip force of 235 N. The robot is used in the pilot studies to validate the design philosophy of using the trackpad on the handheld controller to develop a motion mapping interface capable of precise control. The implementation of the controller motion mapping and button configuration is expanded in **Chapter 5** and **Chapter 7**.

Chapter 4

Prior Work and Lessons Learned[1]

4.1 Identifying the Ideal Teleoperation Interface

4.1.1 Experimental Set-up and Participants

The TRINA robot as described in Section 3.1 with the UBIROS GentleDuo grippers was controlled using three representative teleoperation interfaces: joystick controller (Logitech F710), Stylus based controller (Geomagic Touch) (refer Fig. 4.1) and human motion capture (VICON Nexus) (refer Table 4.1). A user study (N=11), involving nursing students (eight female, 19-21 years old) and registered nurses (one 42 year old male and 2 females 35 and 49 years old respectively), was used to evaluate the aforementioned interfaces. Healthcare workers are involved in this study as involving the potential end users early in the development stage can improve the acceptance of the interface [156].

[1]The work presented in this chapter was done in collaboration with Tsung-Chi Lin from the Robotics Engineering Program at Worcester Polytechnic Institute and under the guidance of Professor Zhi Li from the Mechanical Engineering Department at Worcester Polytechnic Institute. The author was responsible for developing and improving the Vicon Interface, designing the autonomous grasping feature, conducting user studies and recording experimental data.

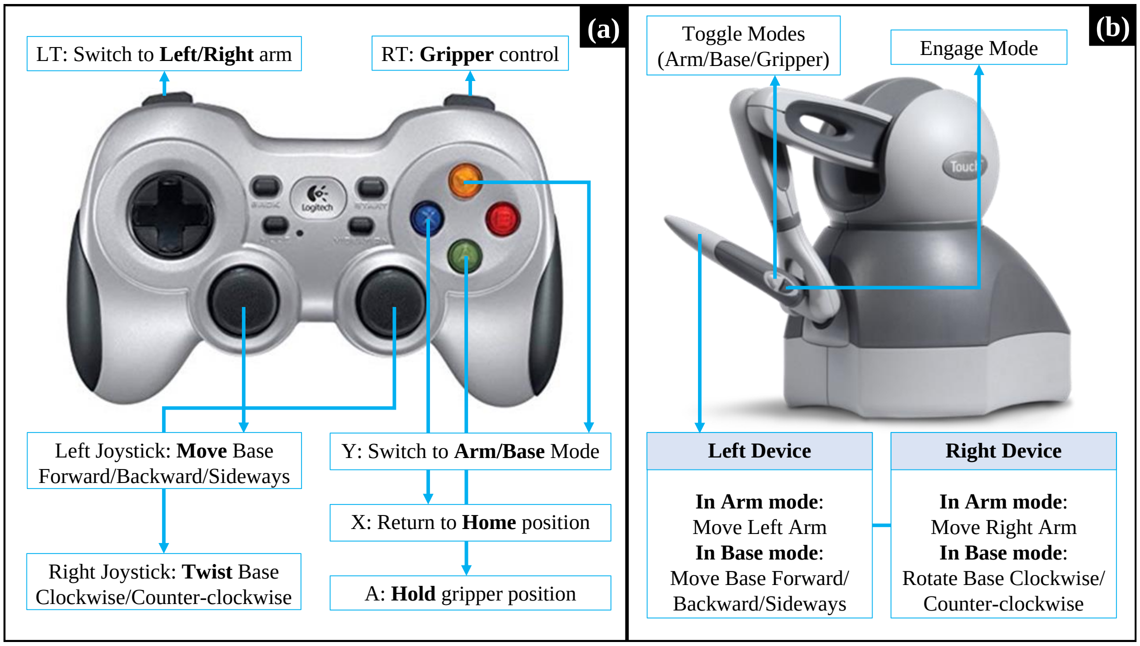

Figure 4.1: Teleoperation controls for (a) Gaempad and (b) Joystick/Stylus interface.

Teleoperation Input	**Robot Function**
	Robot's Upper Body
Hand position and orientation	End-effector position and orientation
Arm posture and orientation	Manipulator arm posture
Rotate upper body	Rotate mobile base orientation
Hand open/close	Gripper opens/closes
Right shank flexion	Activate teleoperation assistance
	Robot's Lower Body
Squat	Engage/Disengage teleoperation
Leg steps forward/backward	Mobile base moves front/back
Left (right) leg steps left (right)	Mobile base moves left (right)
Lift right leg	Switch the camera view

Table 4.1: Motion Mapping Teleoperation Interface. The arm posture is measured by the swivel angle, i.e., the rotation of the elbow position with respect to the axis connecting the shoulder and wrist positions [23].

4.1.2 Experimental Tasks and Procedures

The participants were required to perform two trials of a testing task (Fig. 4.13, left) where they collect an object placed on the workspace table and deposit into a basket.

Figure 4.2: The tasks of the user study include collecting a single object (left) , and cleaning and organizing a counter workspace (right).

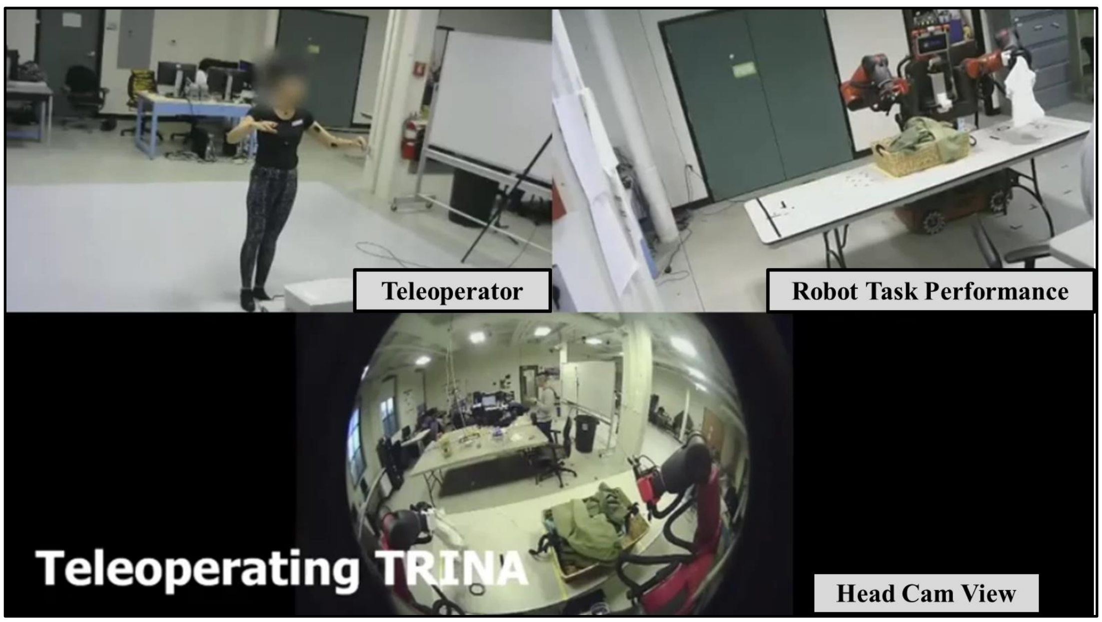

Figure 4.3: Clockwise from top left: The teleoperator in the Vicon workspace, the robot performing tasks and the fish eye camera feed projected in front of the teloperator.

This task is separated by a practice session of a maximum of 15 minutes. The participants are allowed to stop the practice session anytime they feel comfortable using the interface. The amount of time used for practice and the difference in task performance after practice are used to identify the learning effort associated with the interfaces. The evaluation task (Fig. 4.13, right) is performed after two trials of the testing tasks and the participant is required to collect 3 grocery items and 3 pieces of clothing and sorting them into two different baskets. The participants are required to answer several simple arithmetic questions to help identify the cognitive workload associated with the interface. The more complicated the interface the lesser the questions answered per unit time. A subjective workload estimated based on the responses to a NASA-TLX questionnaire after the experiments also helps identify the user's perceived workload and preferences for using the different interfaces.

4.1.3 Results and Discussion

Learning Effort

Fig. 4.4 shows a summary of the practice time used and differences in task completion times before and after practice among both nursing students and registered nurses. Each ellipse in Fig. 4.4 plots the mean and standard deviations of the task completion time against the mean and standard deviations of the practice times used by the nursing student participants during the testing task trials.

The nursing students took less time to learn the motion capture (219 ± 39 sec) interface compared to the gamepad (792 ± 57 sec) and stylus device (870 ± 20 sec) interfaces. These results highlight the lower learning efforts associated with the motion capture interface. The participants utilized a lower amount of the practice time compared to the other interfaces implying this interface was easy to understand and is intuitive providing the participants with the confidence to teleoperate the robot using this interface.

The nursing students also completed the testing task faster using the motion capture interface (61 ± 6.7 sec) compared to the gamepad (90 ± 8.2 sec) and stylus device

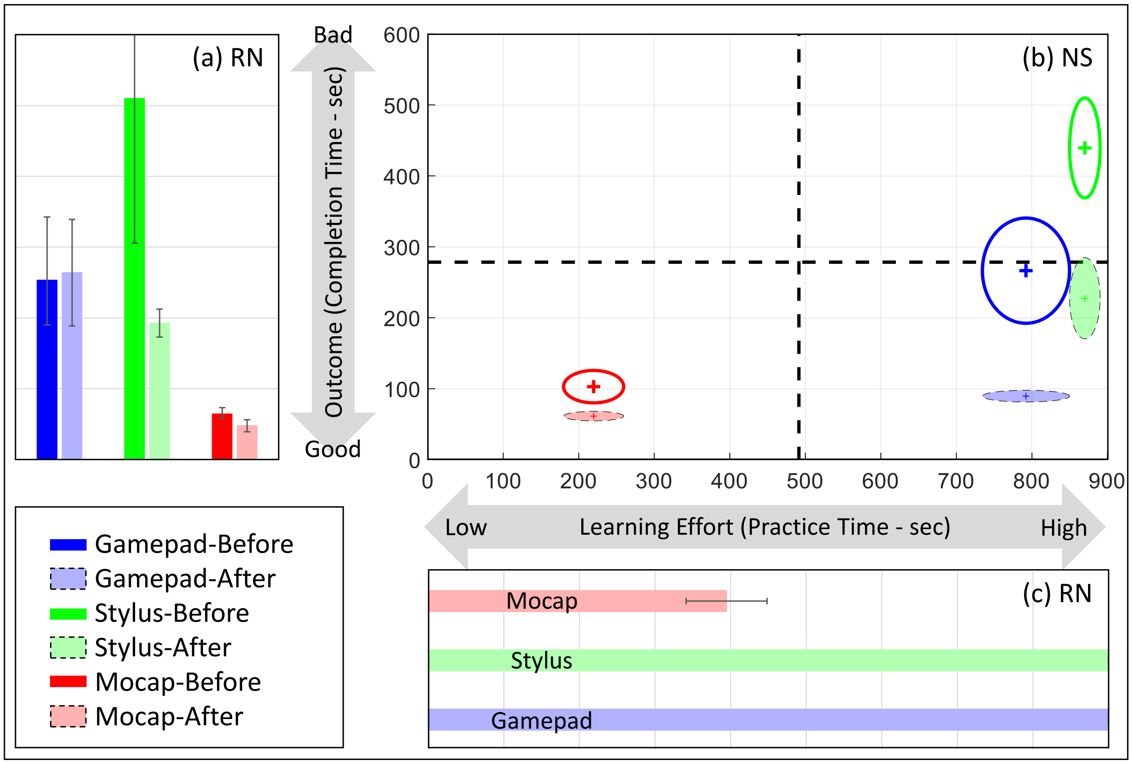

Figure 4.4: Practice time vs Completion time for nursing students (NS) and registered nurses (RN).

(228 ± 57 sec) interfaces. The motion capture interface also facilitated faster completion times in the evaluation tasks as well. It is of note that the motion capture interface showed little improvement before and after practice sessions implying that the interface to begin with was easy to understand and intuitive. Due to the small population of registered nurses no significant conclusions could be inferred. However, these subjects also highlight the intuitive nature of motion capture interface observed among nursing students.

Cognitive Workload

Subjects show similar trends in the task completion times for the evaluation task that involves collecting and sorting of laundry and regular objects. The motion mapping

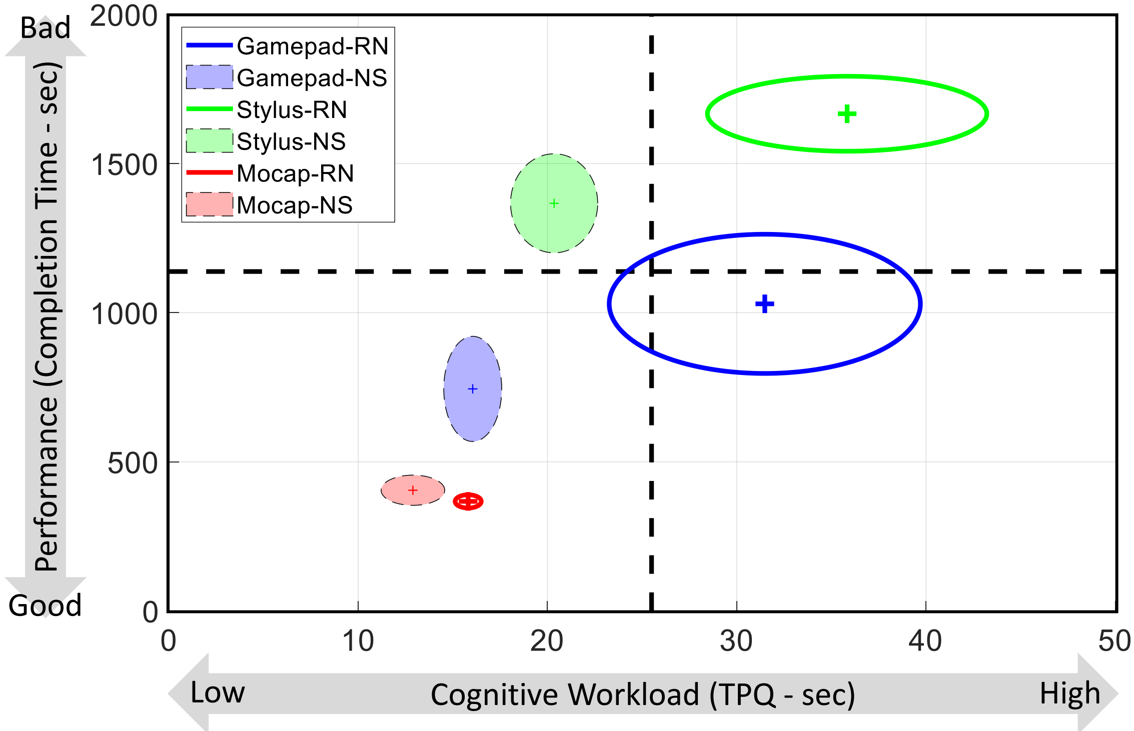

Figure 4.5: Completion time vs Cognitive workload based on the time per question answered for nursing students (NS) and registered nurses (RN).

interface showed the fastest task completion time (404 ± 50 sec) compared to the gamepad (745 ± 176 sec) and stylus device (1367 ± 165 sec) interfaces. This again shows the efficiency of the motion capture system as an interface. As seen in Fig. 4.5, the amount of time required to answer the arithmetic questions was much less while using the motion capture interface thereby allowing for more cognitive workload to be allocated for other patient caring tasks. Motion capture also facilitates more information extraction from the user for teleoperation control and also showed reduced errors in task performance.

User Preference

As seen in Fig. 4.6, the user's preference ratings for the various interfaces according to their responses to a custom questionnaire show a high inclination towards preferring

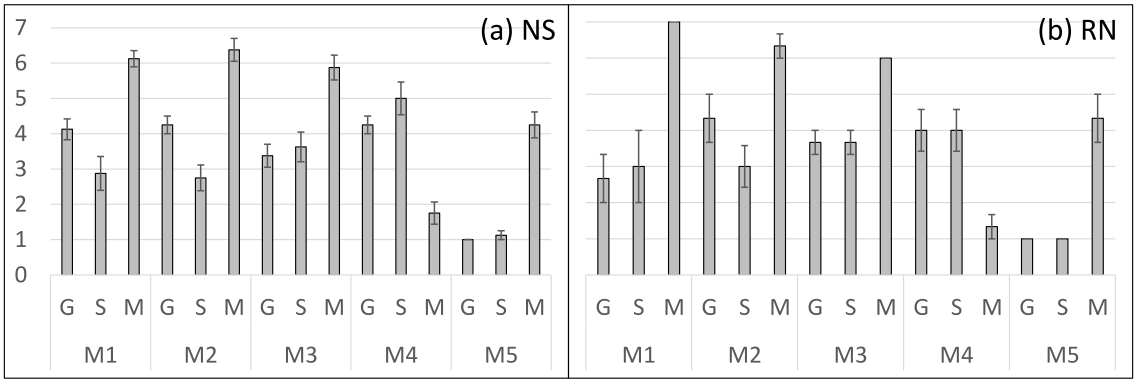

Figure 4.6: Users' preference rating for the gamepad (G), stylus device (S) and motion mapping interface (M) based on controllability (M1), efficiency (M2), accuracy (M3), mental demand (M4) and physical demand (M5).

the motion capture interface for it's controllability, efficiency, accuracy and reduced mental demand. The reason for this might be that if the master and slave arms have a similar kinematic structure, through joint to joint mapping strategy the predictability of the slave arm configuration in response to the input from the master becomes intuitive [44, 45, 46]. Using motions familiar to the user as a way to control the robot rather than using external hardware can make the teleoperation process easier [47, 48]. However, the participants reported increased physical demand while utilizing this interface and mentioned that the physical fatigue was considerable.

4.2 Identifying the Cause for Physical Fatigue [1]

As previously mentioned, while using motion capture as a means of teleoperating, the operators experience non-trivial physical fatigue which will make it detrimental when used for a long time. We further analyse the VICON based motion capture interface which was identified as the most intuitive, easy to learn and efficient interface for the nature and causes of physical fatigue caused in the operator. The physical fatigue is identified by analyzing the EMG signals of targeted muscle groups captured by surface

EMG sensors.

4.2.1 Muscle Effort Analysis using EMG Data

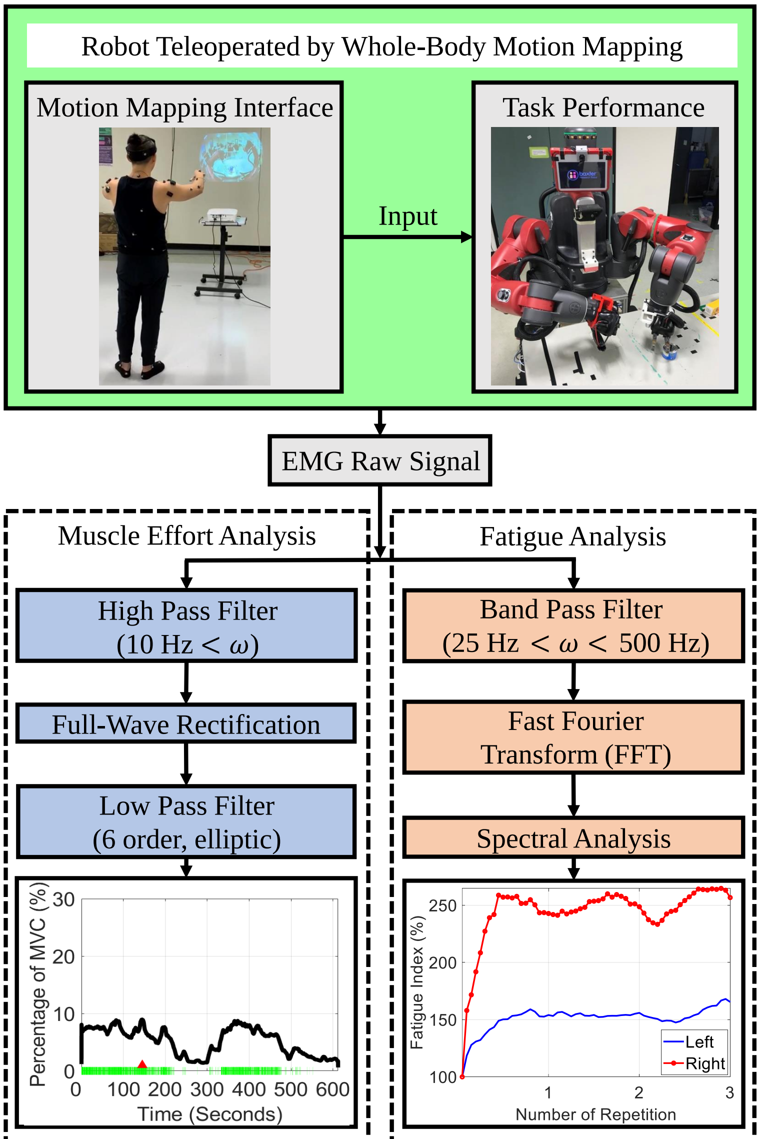

Figure 4.7: Muscle effort and fatigue analysis process.

Fig. 4.7 represents how the EMG data is captured from the teleoperator through sEMG sensors and the different data analysis processes associated with identifying muscle effort and fatigue (refer [1] for more information regarding fatigue analysis procedure).

4.2.2 Experimental Set-up and Participants

The TRINA robot as described in Section 3.1 with the three-finger grippers was teleoperated using the Vicon interface described in Table 4.1 for the purpose of these experiments. Additionally wireless sEMG sensors (Trigno from Delsyss Inc.) are used to record the EMG signals from the Deltoid, Biceps, Brachioradialis, Trapezius and Erector Spinae muscles. These muscles were selected as they are the most important muscles that are involved in the motion of the torso and upper limbs.

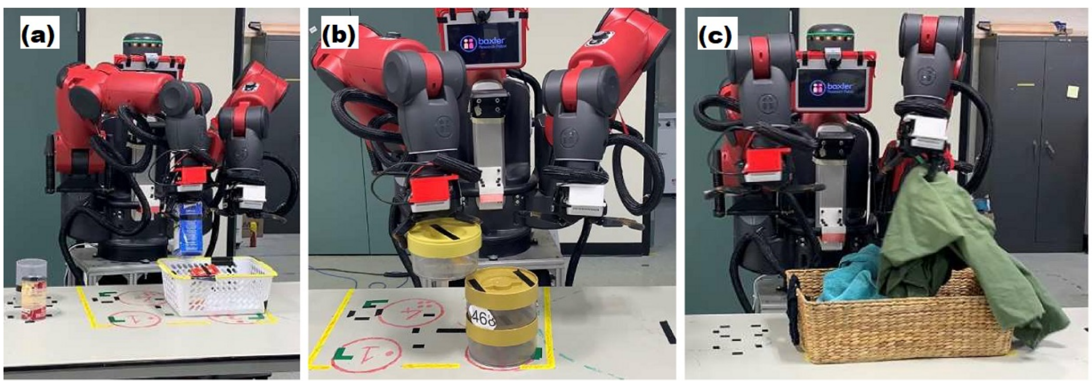

Figure 4.8: Robot teleoperation tasks: (a) Collecting, (b) stacking and (c) laundry.

The experiment involved six male participants (25 ± 3 years) and two female participants (28-29 years old). All of the participants except one of the female participants had a background in engineering. As shown in Fig. 4.8, the participants performed three tasks, namely: 1. Collecting: collect six scattered grocery items scattered on a large table into a container; 2. Stacking: stack food containers in the instructed order; 3. Laundry: collect towels and blankets into a laundry basket and take them out. Each participant performed each of the tasks three times. Prior to the start of the experiments the participants were allowed to become familiar with the the teleoperation interface. MVC tests were conducted on the participants to normalize the EMG signals with respect to the maximum force generated by each muscle, which is identified by this test.

4.3 Results and Discussion

4.3.1 Muscle Effort

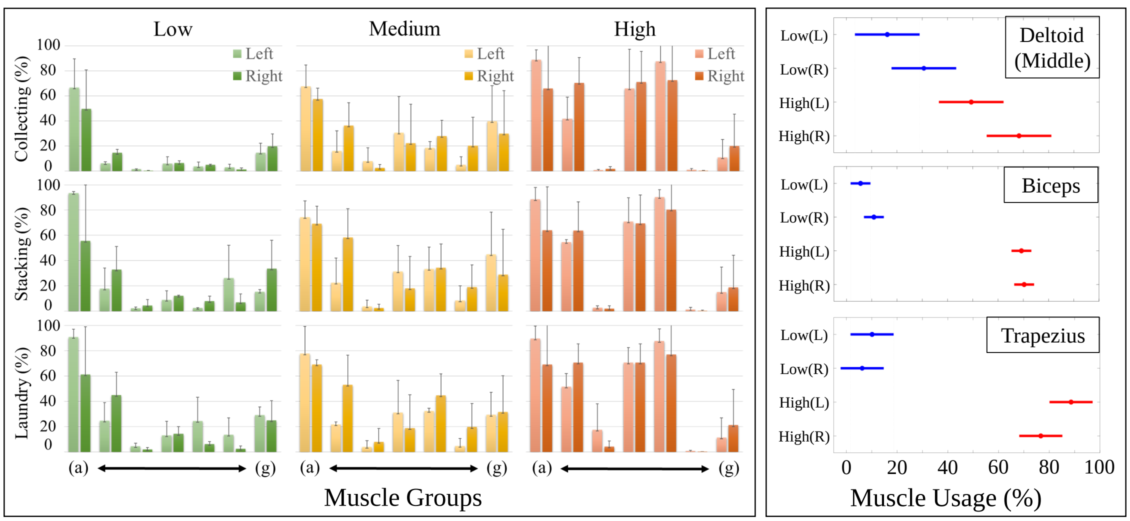

Figure 4.9: The left hand side discusses about the muscle effort comparison among tasks and among muscle groups, including the (a) Anterior Deltoid, (b) Middle Deltoid, (c) Posterior Deltoid, (d) Biceps, (e) Trapezius, (f) Lower back, and (g) Forearm. The right hand section displays the result from ANOVA analysis. The blue lines represent the muscle usage of low muscle usage group and the red line represents the high muscle usage group.

The averaged muscle effort across all participants is represented in the left hand side of Fig. 4.9 based on the EMG data that was collected. Muscle effort is defined as the percentage of the task completion time the muscle effort remains contracted. Based on the muscle effort and muscle usage, the users are divided into lower and higher muscle usage groups. It should be of note that the participants who had previous experience in teleoperation of robots displayed lower muscle usage as compared to novices. Familiarity with interfaces might have enabled the participants to be more efficient with their movements, thereby reducing the potential physical fatigue.

4.3.2 Physical Fatigue

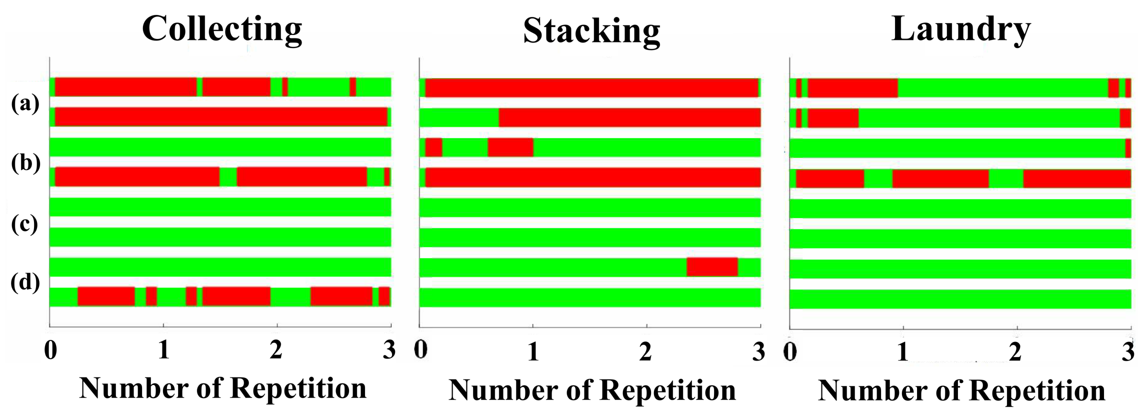

Figure 4.10: Fatigue comparison across tasks.

As seen in Fig. 4.9, the most active muscles during this teleoperation process were: a) Trapezius b) Biceps c) Middle Deltoid and d) Anterior Deltoid. The results show that the Biceps and Trapezius muscle groups were the most fatigued muscles. In Fig. 4.10, the region marked in red identifies the duration in which the fatigue index calculated from the EMG signals was above the pre-determined fatigue threshold as identified in [1]. Also, the stacking and collecting tasks were more fatiguing than the laundry task. This might be because the stacking and collecting tasks involve more finer manipulation involved in picking up smaller objects and holding the camera arm steady to get proper depth perception for manipulation. These inferences were confirmed by the responses of the participants from the user survey results presented in Section 4.3.3

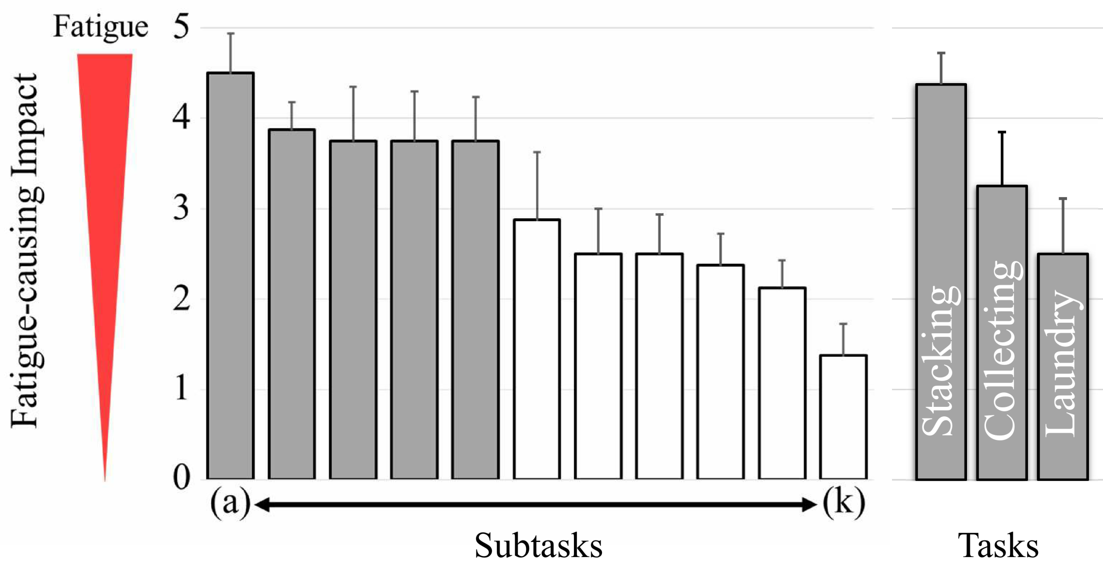

Figure 4.11: Survey results. (a)-(k) are the potential fatigue-causing teleoperation actions (see Section 4.3.3).

4.3.3 User Survey Results

The teleoperation actions that cause more fatigue (rated ≥ 3) include: (a) holding steady pose of the wrist camera for observation, (b) aligning objects, (c) raising arm up for long time during teleoperation, (d) grasping small object, and (e) adjusting camera view for best perspective. The less fatigue-causing actions (rated < 3) include: (f) picking objects from the top, (g) grasping large object, (h) picking up object from the side, (i) placing object, (j) carrying grasped objects, and (k) lifting left to change camera. The users also rated the tasks in the decreasing order of fatigue as follows: Stacking > Collecting > Laundry. These results also confirm the results observed from the fatigue analysis of EMG signals resported in Section 4.3.2.

From these results it becomes evident that manipulation is a crucial part of the teleoperation experience as a lot of effort goes into ensuring a perfect grasp. The operator needs to ensure the correct end effector location of the robot and also ensure the getting the ideal camera view for a complete view of the workspace. Designing a teleoperation interface that either automates the grasping part or is built with ease of grasping objects as the priority might improve the ergonomics of the teleoperation interface.

4.4 Autonomy in Teleoperation and Physical Fatigue [2]

As reaching to grasp objects was identified as a major contributor of physical fatigue causing actions (refer Section 4.2), experiments were designed to verify if automating these actions impacted the teleoperator's performance or physical fatigue.

4.4.1 Automation of Reach to Grasp

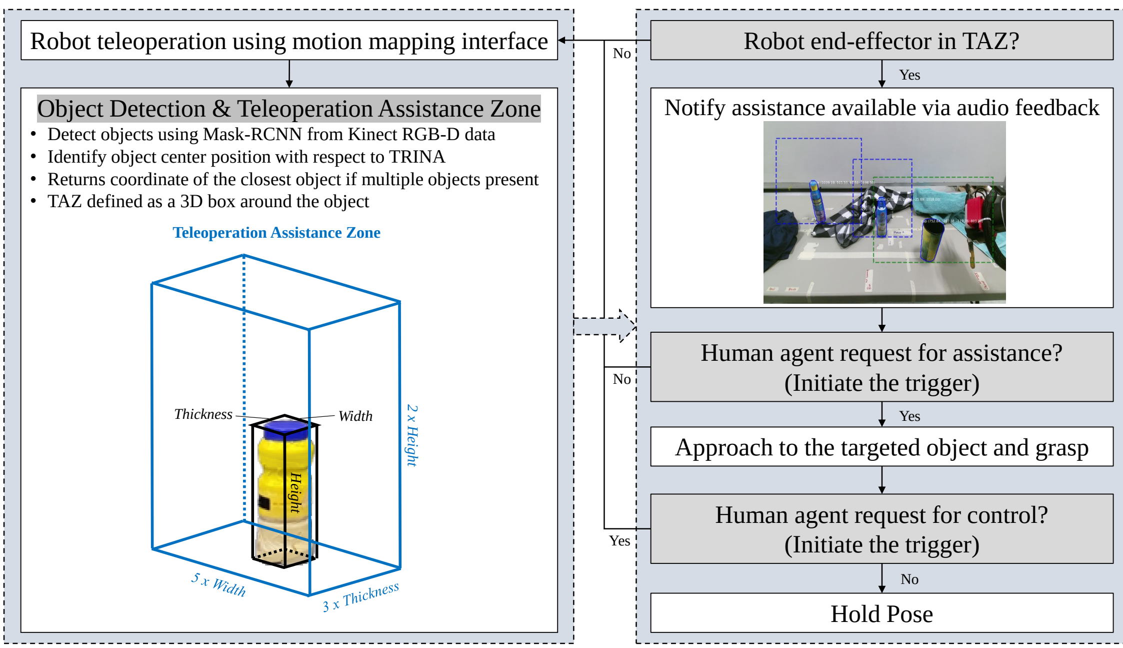

Figure 4.12: Autonomous Grasping Function for Teleoperation Assistance.

Using the Kinect RGB-D cameras mounted on the TRINA robot (refer Fig. 3.1) a computer vision module was developed to detect and locate objects with respect to the robot. A Mask-RCNN model is used to detect the objects from the Kinect RGB-D data [157, 158]. The model forms an initial bounding box around the detected objects which are then expanded to generate a secondary bounding box of (2 × height) × (3 × thickness) × (5 × width) (cm^3) of the original bounding box around the detected object. This region is defined as the Teleoperation Assistance Zone (TAZ). If the end effector is present within this bounding box, then the teleoeprator is notified of the availability of assistance through auditory and visual cues. If multiple objects are detected the object closest to the robot is chosen by default as the object to be picked up. The operator can command when to engage and disengage the assistance feature as explained in Table 4.1. The entire process is summarized in Fig. 4.12.

4.4.2 Experimental Set-up and Participants

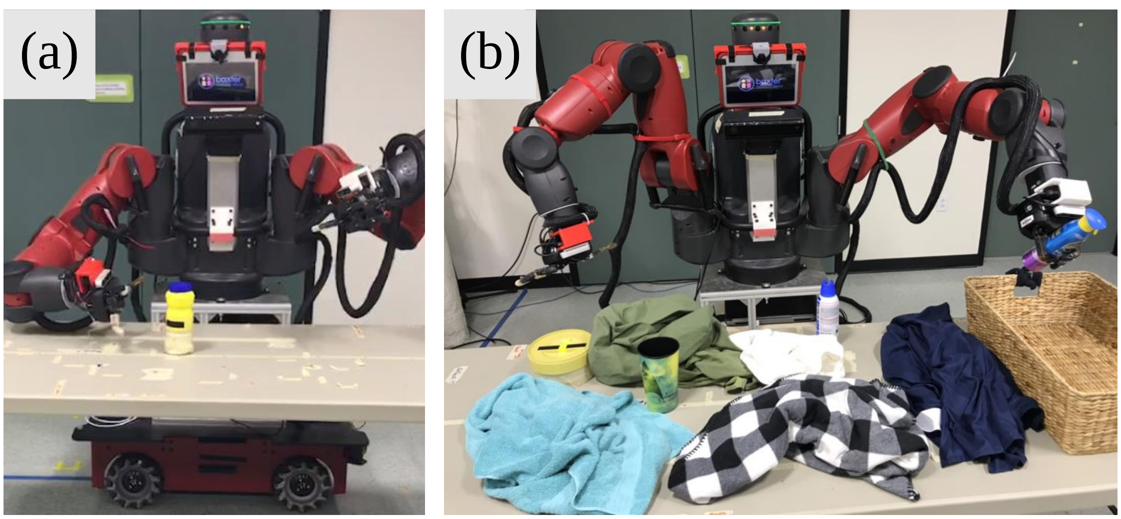

Figure 4.13: Teleoperation tasks: (a) reaching-to-grasp an individual object; (b) collecting multiple objects in a cluttered counter workspace.

A user study consisting of 6 male and 2 female participants teleoperated the TRINA robot (refer Section 3.1) using the motion capture interface with teleoperation assistance described in Table 4.1. All participants were right handed. The experiment consisted of two tasks: 1) Reaching to grasp a single object and 2) Sort objects and laundry into two seperate baskets. The task 1 was performed using both arms with five trials of the task for each arm. The muscle effort to identify the impact of autonomy on the physical workload of the interface was obtained using the methods mentioned in [1] and Fig. 4.7. In task 2, the participants receive +10 points for correctly picking and placing the objects in the desired locations and are penalized -20 points for knocking down or dropping an object. The participant is allowed to pick up the object if they dropped it. However if the object is dropped out of the workspace, then these points are lost.

4.4.3 Results and Discussion

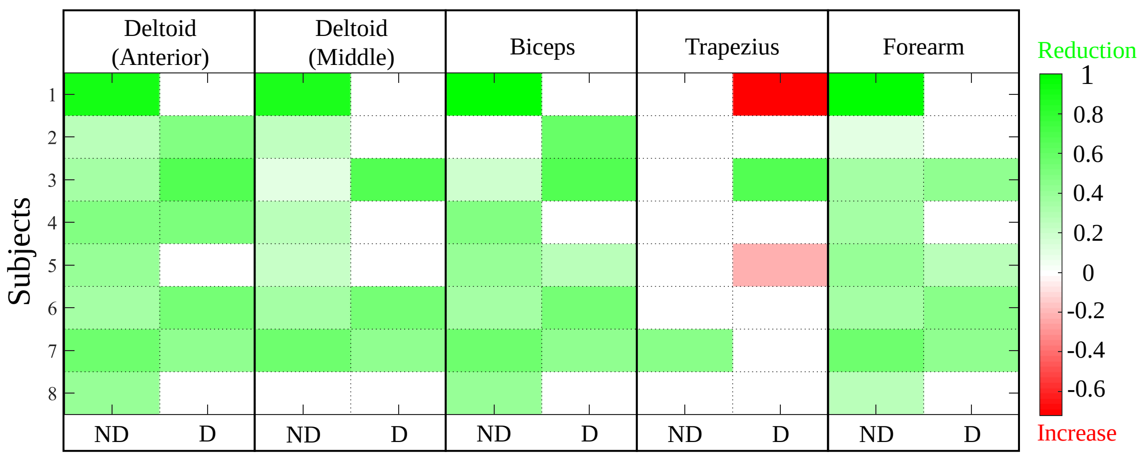

Figure 4.14: Comparison of physical effort across all muscles with dominant (D) and non-dominant (ND) hand.

As seen in Fig. 4.14, the automation of reaching to grasp has reduced the muscle effort in almost all muscle groups, with only the trapezius showing increased muscle effort in one subject in task 1. This helps conclude that simplifying the object grasping task has significantly improved the ergonomics of the teleoperation interface by reducing the muscle effort across the muscle groups.

As seen in Fig. 4.15, the use of the grasping assistance has reduced the task com-

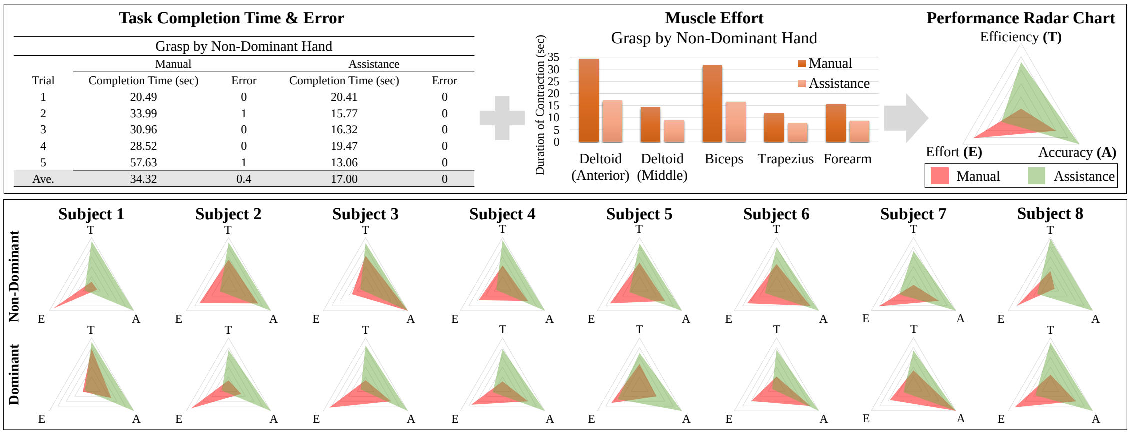

Figure 4.15: Performance evaluation procedure and summary for object grasping across all subjects.

pletion times as well as the errors that occurred while teleoperating TRINA to perform task 1. Overall grasping without teleoepration assistance took 13.3 seconds longer for the non-dominant arm and 11.9 seconds longer for the dominant arm when averaged across all participants. With reduced errors due to the improved accuracy provided by the teleoepration assistance, task completion times decreased.

Performance of Collecting Task										
	Objects Picked		Points-Pick up		Points-Drop in bin		Penalty-Drop Object		Total	
Subject	Manual	Assistance	Manual	Assistance	Manual	Assistance	Manual	Assistance	Manual	Assistance
1	0	3	0	30	0	30	0	0	0	60
2	2	1	30	10	20	10	-20	0	30	20
3	0	3	0	30	0	30	0	0	0	60
4	2	1	10	10	10	10	-20	0	0	20
5	1	2	10	20	10	20	0	0	20	40
6	2	1	20	10	10	10	-40	0	-10	20
7	1	2	10	20	0	20	0	0	10	40
8	0	3	0	30	0	30	0	0	0	60
Sum	**8**	**16**	**80**	**160**	**50**	**160**	**-80**	**0**	**50**	**320**

Table 4.2: Performance of score system for collecting three objects.

Through the task 2, we observe that participants who used teleoepration assistance more were able to accrue more points. This was again a result of the greater accuracy that the grasping assistance provides. For this task the participants were allowed to decide if they wanted to use assistance for grasping or not. Overall, we observed that more participants preferred to use teleoepration assistance. The particpants' responses to a post-study survey postively rated the teleoepration assistance's ability to increase successful grasping, reduce the task completion time, reduce cognitive workload and physical workload. The participants also reported that teleoperation assistance improved their opinion about teleoperated robots and their preference for such interfaces.

Manipulation contributes to a substantial amount of fatigue while teleoperating and automating it has improved the interface objectively and subjectively. It is therefore useful to design an interface that caters to simplifying the act of grasping. In conventional day-to-day nursing tasks, interacting with and picking up objects play a crucial role. An in-depth look of the design implementation of such an interface for the two robots mentioned in **Chapter 3** and its validation is described in **Chapter 5**, **Chapter 6**, **Chapter 7** and **Chapter 8**.

Chapter 5

Defining the Vive Workspace

In order to translate the motion from the HTC Vive controllers to control the end-effectors of TRINA or the Gen3 arm, the coordinate frames of the hand-held controllers must be aligned in the same way as the end-effector's frames are with respect to the base TRINA or Kinova Gen3 frame. This will ensure that the motion is mapped from the controller to the end-effector as intentended in an intuitive and efficient manner.

5.1 Establishing the Location of the Vive Base Frame

The first step is to establish the position of the desired origin of the Vive workspace with respect to the primary lighthouse of the Vive system. The origin is where the operator is designated to stand while operating the robot. The x, y and z coordinates of this point relative to the Principal lighthouse is used while launching the lighthouse motion trackers. This information is required to establish the location of the Vive base frame with respect to the Principal lighthouse to ensure accurate tracking (refer Fig. 5.2). The location of the Vive Base Frame is where the operator is expected to stand.

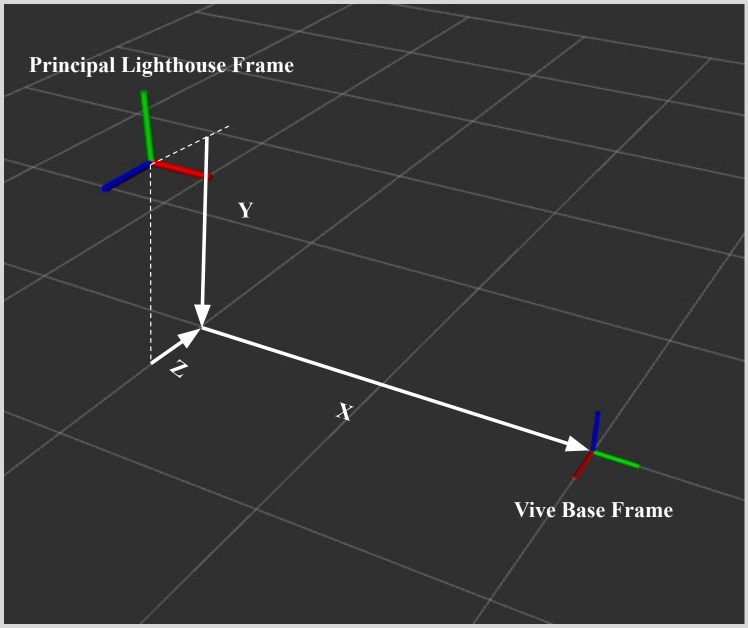

Figure 5.1: The offsets of the Vive Base Frame with respect to the Principal lighthouse frame in the X, Y and Z-directions of the lighthouse frame are denoted as X, Y and Z. These parameters are required to launch the Vive interface to establish the location of the Vive base frame with respect to the Principal lighthouse to ensure accurate tracking.

5.2 Establishing the Orientation of the Vive Base Frame

The origin of the system is based only on the location and orientation of the primary lighthouse and is not dependant on the way the other lighthouse is positioned. Also the initial Vive frame created at the origin of the Vive workspace is rotated by $-90°$ along the z-axis of original the Vive base frame as seen in Equation 5.1, Equation 5.2 and Fig. 5.2. By doing so, all the frame transforms of the controllers will be done with respect to the original TRINA base frame's orientation. This eliminates the need for individual frame transforms to the TRINA base frame reducing computation cost. The Gen3 Jaco arm's base frame is also oriented in the same way as the Trina base frame and these frame transformations apply for the Vive interface when controlling the Jaco arm too.

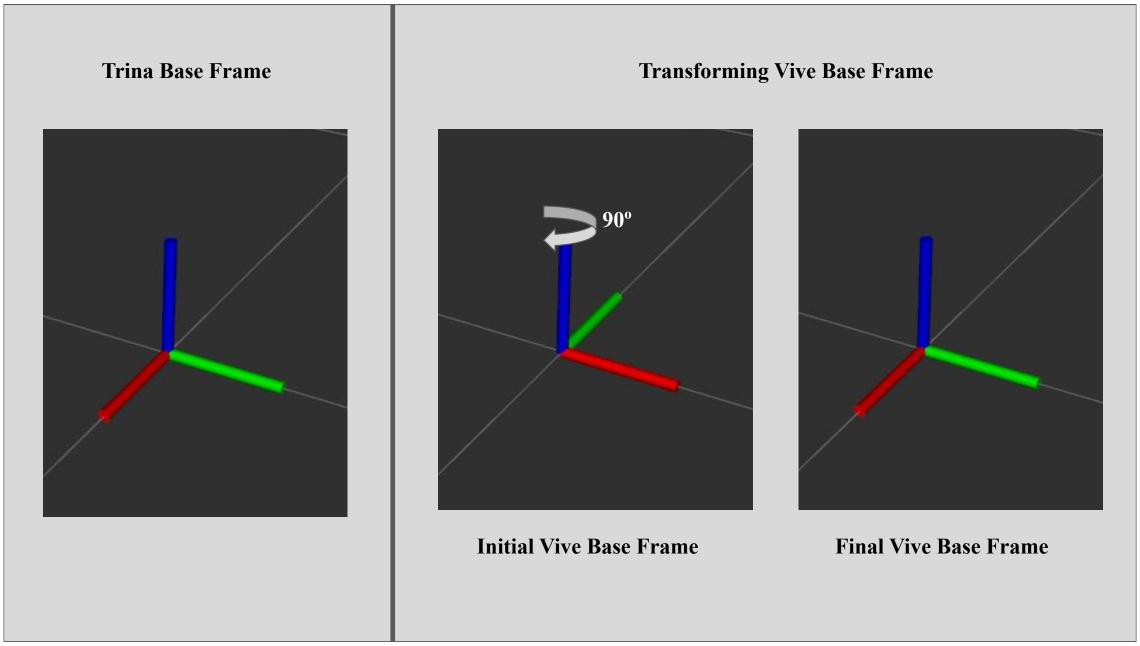

Figure 5.2: Rotating the default Vive Base Frame configuration to match the TRINA and Jaco arm Base Frames.

$$R_{VO}^{RB} = R_{VB}^{PL} \times R_z(-90°) \tag{5.1}$$

$$R_{VO}^{RB} = R_{VB}^{PL} \times \begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{5.2}$$

where,

R_{VO}^{RB}: Rotation matrix of frame at Vive Origin with respect to Robot Base Frame

R_{VB}^{PL}: Rotation of Vive Base frame with respect to frame at the Primary Lighthouse

R_z: Rotation with respect to z-axis

The controller's default orientation is at an angle to the TRINA base frame and requires to be calibrated such that the frame of the VR controller matches the robot end-effector frame when the handle of the VR controller is parallel to the floor and pointing forward. This calibration is done with the primary lighthouse looking straight forward while the other lighthouse is set-up to ensure it has a substantial view of the operator's workspace to ensure repeatability.

The x,y and z coordinates of the controller in the Vive workspace are linearly scaled to the TRINA workspace (Equation 5.3, Equation 5.4 and Equation 5.5). As the dimensions of the TRINA arms are longer than the operator's arm, the desired x and y coordinates from the Vive system is increased in value to augment the operator's smaller limbs. This calibration of the workspace can be automated in future iterations to tailor the workspace to the operator's dimensions.

$$x_{TRINA} = 1.276 \times x_{Vive} \tag{5.3}$$

$$y_{TRINA} = 1 \times y_{Vive} \tag{5.4}$$

$$z_{TRINA} = 1.109 \times z_{Vive} \tag{5.5}$$

where,

x_{TRINA}, y_{TRINA} and z_{TRINA}: x,y and z coordinates in TRINA workspace

x_{Vive}, y_{Vive} and z_{Vive}: x, y and z coordinates in Vive workspace

The Vive interface for the Kinova arm uses velocity control instead of the position control used in developing the Vive interface for the TRINA. This was done to use the default Kortex-API provided by Kinova Robotics for the control of the Gen3 Jaco arm [159]. As a result the workspace augmentation done to fit the robot arm dimensions as in the case of TRINA is not required, as the desired location of the object is not required when mapping the velocity of the controller to the end-effector.

Chapter 6

Vive Interface Controls for TRINA

Tele-nursing robots are controlled through a teleoperation interface that should be versatile and intuitive so that the teleoperator, usually an healthcare worker, can easily operate the robot.

Capturing the human motion and mapping it to the robot results in an intuitive and easy to comprehend interface as described in **Chapter 2** and **Chapter 4**. The developed interface was designed with this idea as it would reduce the learning curve associated with this interface and the cognitive workload while teleoperation will be minimal Section 4.1.

Grasping objects during teleoperation is a particularly demanding task as seen in Section 4.2. This action involves multiple tiring sub-tasks like steady posture maintenance and fine manipulation.

The interface was designed with the intuition that objects will be picked from the sides and the pose of the robot end-effector in the default orientation of the controllers must be in a way that facilitates this action (refer Equation 5.2 and Fig. 6.1). Since one of the most common activities during teleoperation is to reach and collect objects, designing the interface to fast-track grasping by having the end-effector at the most common grasping pose by default reduces wasted motion from the operator. This eliminates the need for all the adjustments in position and orientation that are required from the users while performing grasping, reducing the resulting fatigue and improving teleoperation ergonomics.

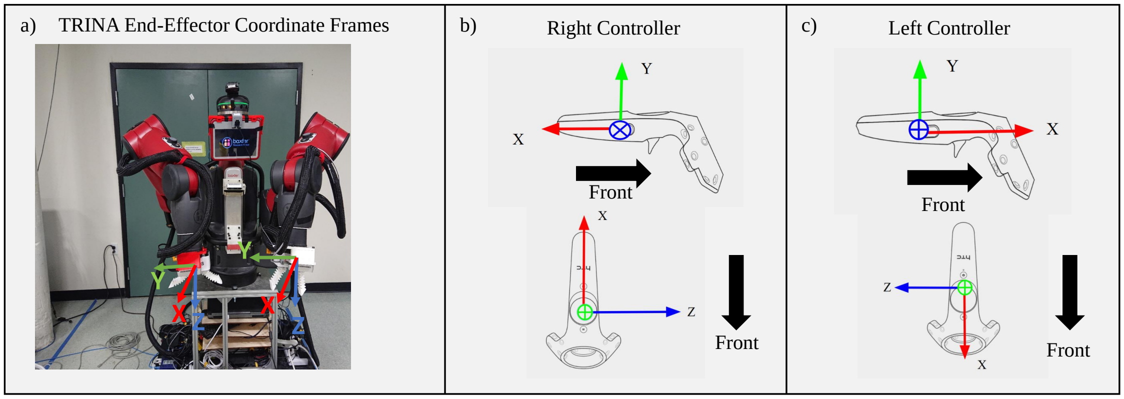

Figure 6.1: Mapping of Frames from the controllers to the robot's right and left end-effectors.

The TRINA's end-effector replicates the pose of the operator's hand while they hold the controller. Having the user learn to match their hands's pose with the end-effector's pose makes the interface becomes more intuitive. The user can identify that the end-effector moves like their hand and don't have the added degree of complexity of having to map the controller's orientation to the robot's end-effector. Fig. 6.1 a) represents the how the right end effector is mapped with respect to the right hand controller. The frames are rotated by 180° along the y-axis to form the mapping of the frames of the left hand controller to the left end-effector as seen in Fig. 6.1 b). Thus, the operator can think of holding the robot end-effectors as a tool and guiding it to perform various operations.

The position of the controllers in the Vive workspace defined in **Chapter 5** are then modified to to the scaled Vive workspace mentioned in Equation 5.3, Equation 5.4 and Equation 5.5. These new coordinates are the desired locations of the TRINA end-effectors in the TRINA workspace and the corresponding joints and end-effector move to this location based on the Inverse Kinematics solution for this location. The coordinate end-effector frames are designed to rotate in the same way the coordinate frames on the Vive controllers are rotated. The Inverse Kinematics solver accounts for this rotation of the end-effector as well when determining the solution for this target end-effector location and orientation.

6.1 Button Configuration

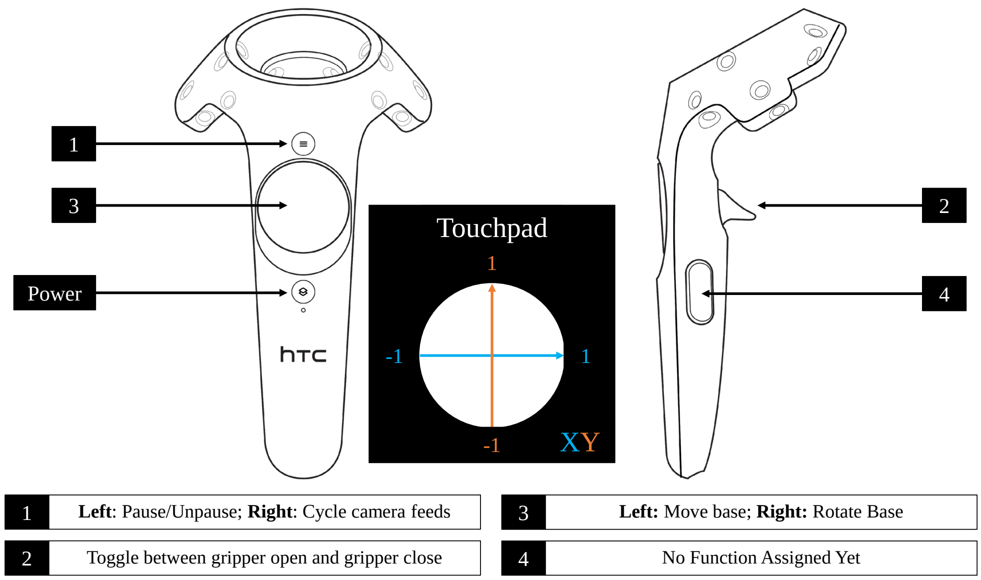

Figure 6.2: The Button configuration to control different functions of the robot.

The controller configuration is as shown in Fig. 6.2. While the motion of the controllers control the position and orientation of the robot end-effectors, the buttons on the controllers control the different functions of the robot.

$$V_{base} = \sqrt{x^2 + y^2} \tag{6.1}$$

where,

x: x-coordinate of the input from the touchpad

y: y-coordinate of the inpute from the touchpad

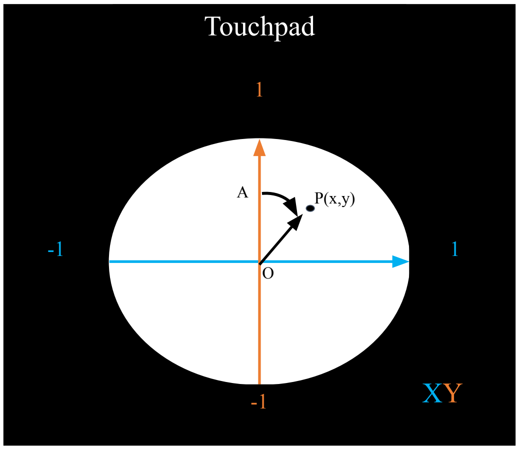

Figure 6.3: Translating the operator's input on the touchpad to mobile base motion.

On the **Left Controller**, button 1 (refer Figure 6.2) lets the user pause or disengage and unpause or engage the robot. Pressing down on the left touchpad moves the robot base forward, backward and sideways based on where the finger is on the touchpad. The operator is required to press down on the touchpad to prevent them from accidentally moving the base. Since the base is omni-directional it can move in any direction as the touchpad can facilitate the information for such motion.

In Figure 6.3, Points O and P are the origin of the touchpad and the point of contact of the user on the touchpad respectively. Line segment OP represents the trajectory in which the base will move and the length of the line segment represents the magnitude of the velocity of the base as shown in Equation 6.1.

On the **Right Controller**, the user can rotate the mobile base. The point where the user presses down denotes the direction in which the robot will rotate. As seen in Figure 6.3, $\widehat{AB}$ denotes the direction in which the base will rotate while the length of line segment OP represents the speed with which the robot rotates (refer Equation 6.1). By separating the linear and angular motion of the robot, the user doesn't accidentally rotate or move the robot base.

Initial pilot testing indicated that implementing the gripper control as a switch was the more appealing option. The users as a result no longer have to be conscious of the gripper control beyond the scope of turning opening and closing the robot hand.

6.2 Communication with the Robot

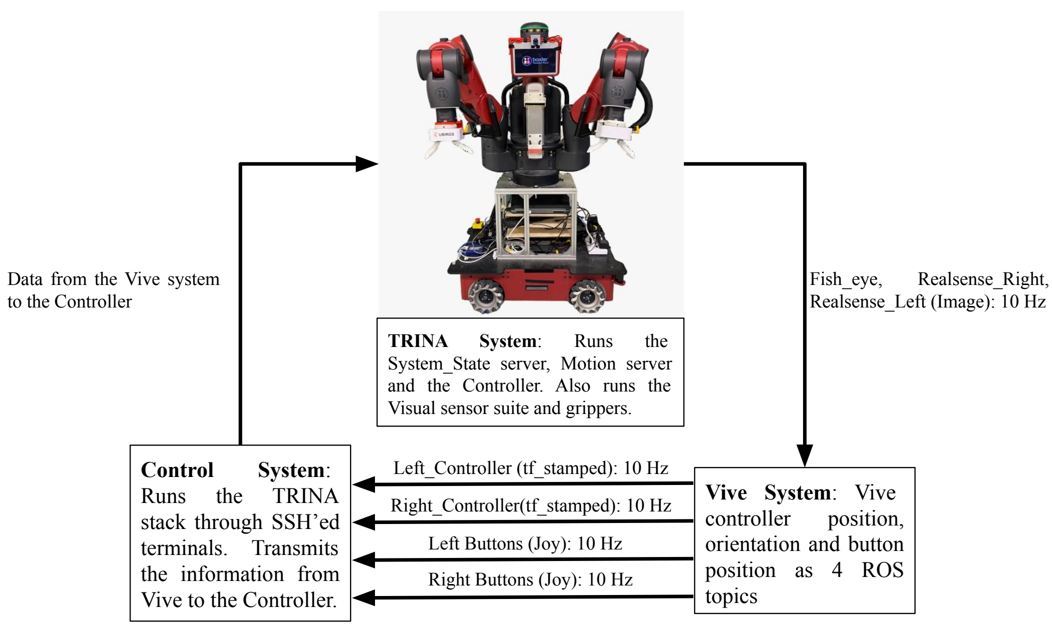

Figure 6.4: The figure above represents the Communication setup between TRINA and the Vive system.

The System_State server, Motion server and the Controller stack in the TRINA system is responsible for handling the motion of the TRINA robot system based on the motion commands it receives from the Vive system and the Control system.

The information from the Vive controllers is sent to the TRINA robot using ROS (Robotic Operating Software)[160] topics. The position and the orientation of the Vive controllers are sent to the robot as a "TransformStamped" message [161] while the information from the Vive button is sent as "Joy" messages [162].

This information from the two controllers is sent to the TRINA robot at a rate of 10 Hz.

Chapter 7

Vive Interface Controls for Gen3 Jaco

The intuition of grasping objects from the side did not work while designing the interface for this robotic arm as the design of the arm and the lack of a second arm severely restricted the usable workspace while teleoperating the robot in this orientation. As a result, the default orientation of the robotic arm with respect to the default orientation of the VR controller is as shown in Fig. 7.1. The Vive workspace is the same as the one defined in **Chapter 5**. With this orientation, where the end-effector is above the workspace and pointing down, it makes it easier for the operator to pick up objects from the top. This is beneficial if the objects being manipulated are small objects which cannot be picked from the sides. However, if an object is large enough to be picked from the side, the intuitive nature of motion mapping enables the operator to re-orient the end-effector easily to this position to pick up the object.

In order to use the API provided by Kinova Robotics to control the Gen3 robot arm, Velocity control was used to control the robot end-effector. The velocity with which the the controller is moved in the x, y and z-directions as shown in Fig. 7.1 is mapped to the robot end-effector's x,y and z-directions.

The rotation of the the end-effector is controlled by a the velocity with which the

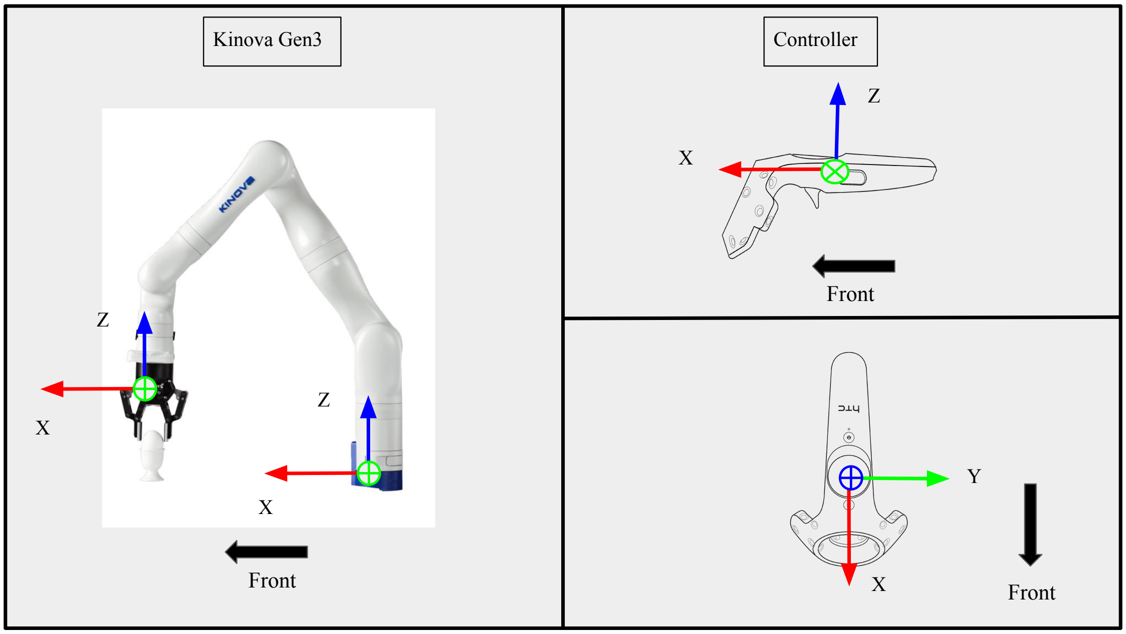

Figure 7.1: Mapping of Frames from the controllers to the robot's end-effector.

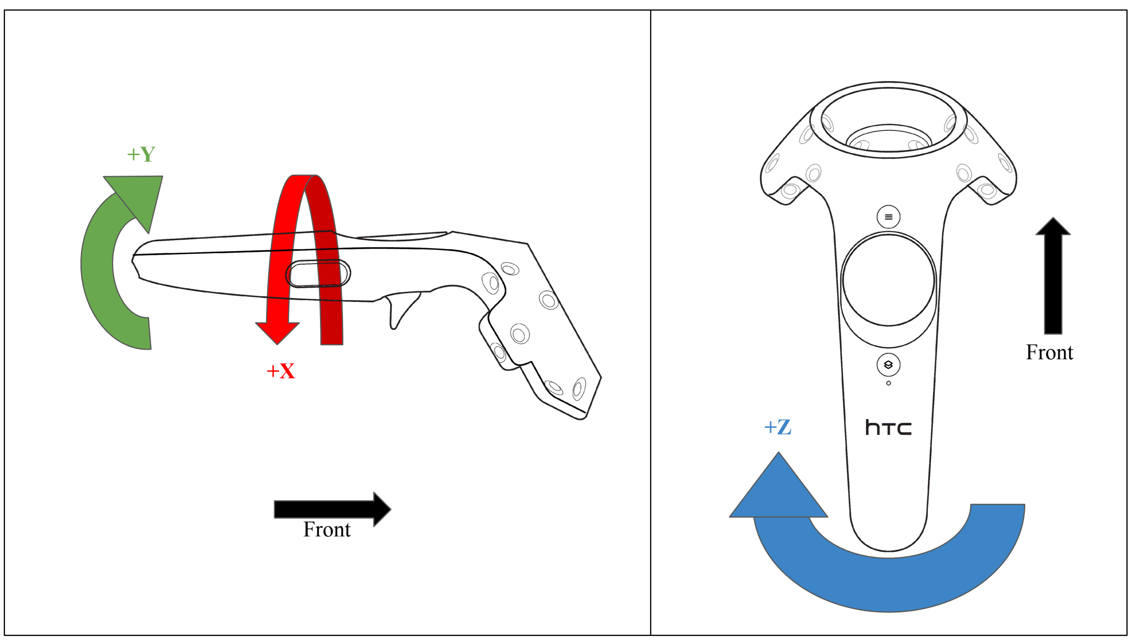

Figure 7.2: The end-effector is rotated about the x, y and z-axes based on the motion of the Vive controller denoted by the arrows.

controller is rotated replicating a joystick like mechanism in 3-dimensions. A filter of 20° was placed to ensure that accidental rotations in other axes don't happen while controlling angular motion in one direction. Movement in the opposite direction while controlling the orientation is possible only by moving in the opposite direction and moving past the default orientation of the controller, which is having the handle parallel to the floor.

As the interface is tracking the controller velocity and not the motion of the controller this interface provides the user the option to reset themselves. This means, the user can pause the interface and get back to a comfortable position before resuming teleoperation.

7.1 Button Configuration

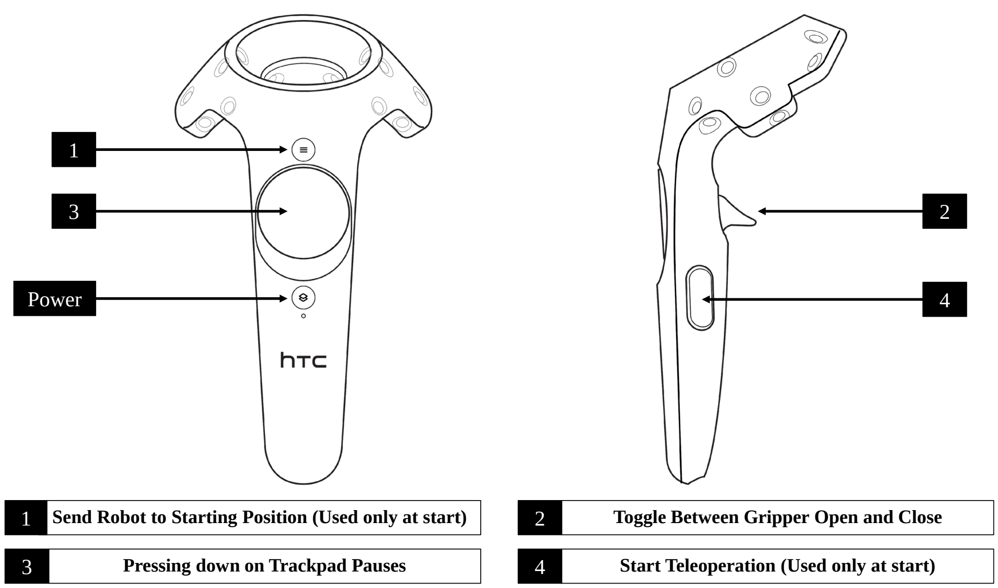

Figure 7.3: The Button configuration to control different functions of the robot.

The Button configuration for the Vive interface for the Kinova arm is as seen in Fig. 7.3. However, as noted earlier motion mapping as an interface suffers when having to handle fine tasks as it cannot generate motion commands that are discrete and minute. As a result the aforementioned interface was augmented by improving the trackpad functionality beyond acting just as a pause button.

7.2 Trackpad Control Mode

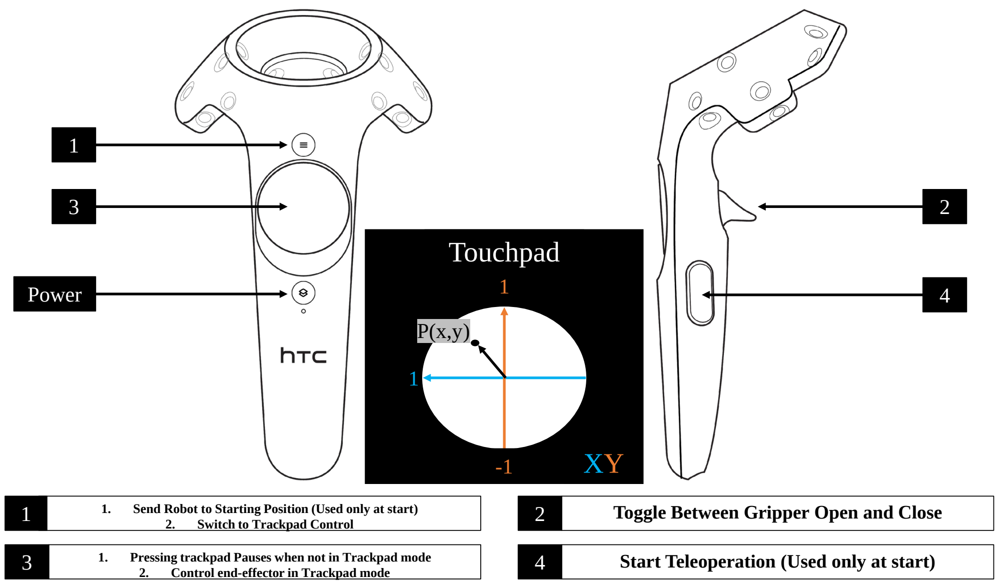

Figure 7.4: Button and Trackpad configuration for the Vive interface for the Kinova arm.

In the Trackpad Control Mode the operator can control the end-effector using the trackpad. This allows the operator to perform precise movements with the robot when the situation demands as the operator can provide small and discrete motion commands using the trackpad.

The x and y values are the coordinates of where the operator's fingers are placed on the trackpad. The x and y values when the finger is placed on the trackpad moves the end-effector in the x and y-directions shown in Fig. 7.1. When the trackpad is pressed down, the end-effector moves in the z-direction based on the x-value alone. The trackpad doubles as the pause button and the end-effector controller when in the Trackpad Control Mode. The operator does not need a dedicated pause button when in the Trackpad Control Mode as the robot moves only based on input from the trackpad and if the operator does not use the trackpad, the robot does not move. This essentially serves as a pause. The performances of both varieties of the Vive interface for the Kinova arm is reported in Section 8.2.

7.3 Communication with the Robot

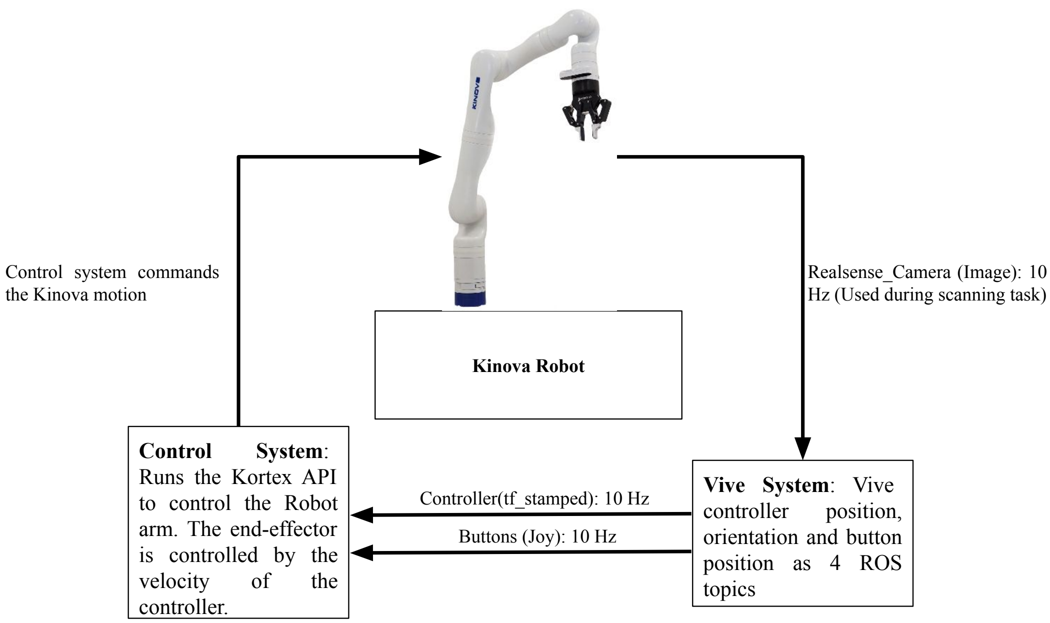

Figure 7.5: The figure above represents the Communication setup between Gen3 arm and the Vive system.

The Kortex API [159] is used to send the motion commands to the Kinova robot and control it's motion. Velocity control is used to control the robot end-effector's motion. The difference between two controller locations seperated by 10 time steps and the rate at which the information is transferred to from Vive to the Control system is used to calculate the controller velocity. This is used to control the robot end-effector as described in the previous section.

The information from the Vive controllers is sent to the Gen3 robot using ROS (Robotic Operating Software) [160] topics. The position and the orientation of the Vive controllers are sent to the robot as a "TransformStamped" message [161] while the information from the Vive button is sent as "Joy" messages [162].

This information from the controllers is sent to the Gen3 robot at a rate of 10 Hz.

Chapter 8

Pilot User Studies

The experimental protocol was reviewed and approved by the Worcester Polytechnic Institute Institutional Review Board (IRB Numbers: IRB-19-0012 and IRB-21-0004).

8.1 Comparison of the Vive and Vicon interfaces

As stated in Section 4.1, the motion capture interface developed using the Vicon Nexus proved to be the most intuitive and easy interface with a low cognitive workload. To understand the usability of Vive interface in comparison with this proven interface, a pilot user study with the TRINA robot platform was performed.

8.1.1 Experimental Setup

The Vicon interface is as described in Section 4.1, Fig. 4.3 and Table 4.1 without the autonomous feature. The Vive interface for TRINA is as mentioned in **Chapter 6**. The teloperator receives a real time video stream from the fish-eye camera of the robot workspace similar to how it is presented in Fig. 4.3. The operator is required to do different tasks that require the user to pick and place objects scattered on the robot

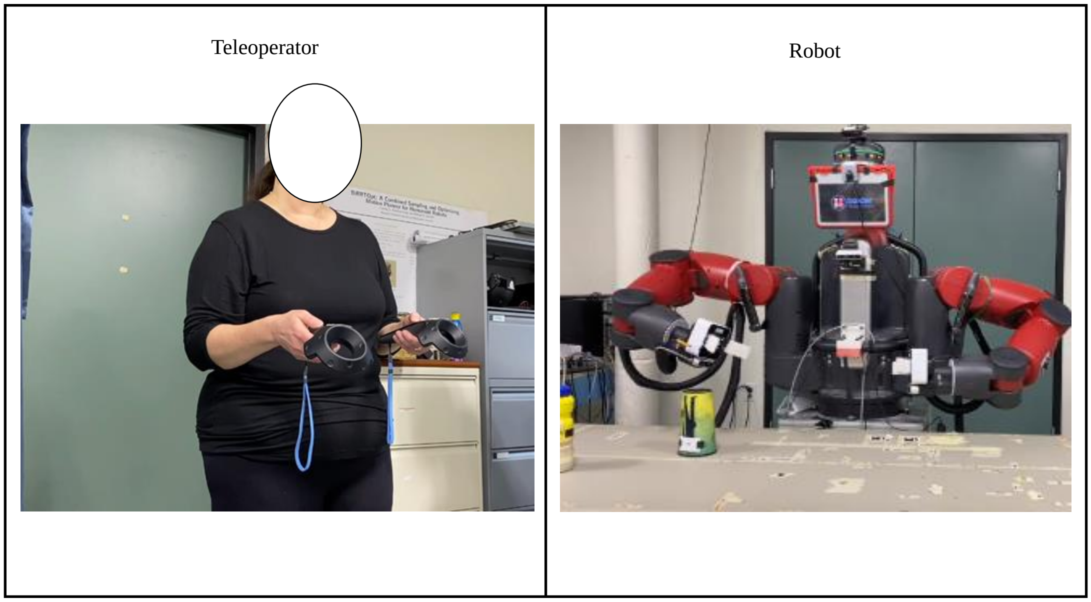

Figure 8.1: The teleoperator operates the TRINA remotely such that they cannot see the robot.

workspace and to control perception cameras on the robot's hands.

8.1.2 Participants and Tasks

Participants

The pilot study involved (N=2) participants who were involved in the development of both the Vicon and Vive interfaces. The participants are familiar with operating the TRINA robot with both the interfaces.

Tasks

The participants performed two tasks, namely the *collecting* and the *scanning* task (refer Fig. 8.3). In the *scanning task* (refer Fig. 8.3 a)), the teleoperator must read the different number labels stuck on five different objects scattered on the table workspace. For reading the number labels, the operator is required to handle the object through

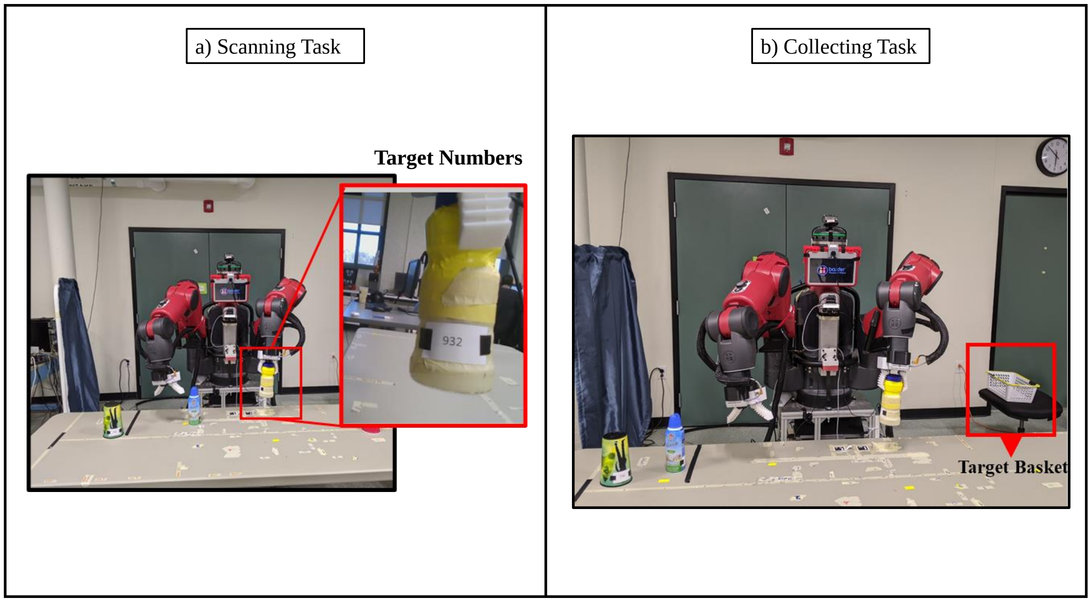

Figure 8.2: The tasks in the pilot study: a) Scanning Task b) Collecting task.

one hand and use the camera on the other hand to view the object and search or scan for the number label. This task tests the user and the interfaces ability to re-orient the end-effector and allow for free-form teleoperation. It also puts emphasis on bi-manual teleoperation, something that an healthcare worker would be required to perform while performing their tasks. An intuitive and easy to use interface is required to make this task easy to execute. One trial for this task was performed by both subjects and the task completion time was recorded. In the *collecting* task (refer Fig. 8.3 b)), the teloperator must collect 3 objects randomly placed in the workspace and place them in a basket placed away from the table workspace. The basket is placed in a location such that the operator is required to rotate and move the robot thus putting an emphasis on locomotion in addition to manipulation. The task also places emphasis on grasping and manipulating while picking up objects. Based on our results from identifying physical fatigue (refer Section 4.2) while teleoperating using the motion capture interface, we observed that grasping and manipulating to pick up objects were among the most fatigue causing actions. Since picking up objects and handling objects is the most common actions while performing nursing task, the interface must allow the operators to teleoperate the robot to perform this action easily. Similar to the previous task, one trial was performed by both subjects and the task completion time was recorded.

8.1.3 Results and Discussion

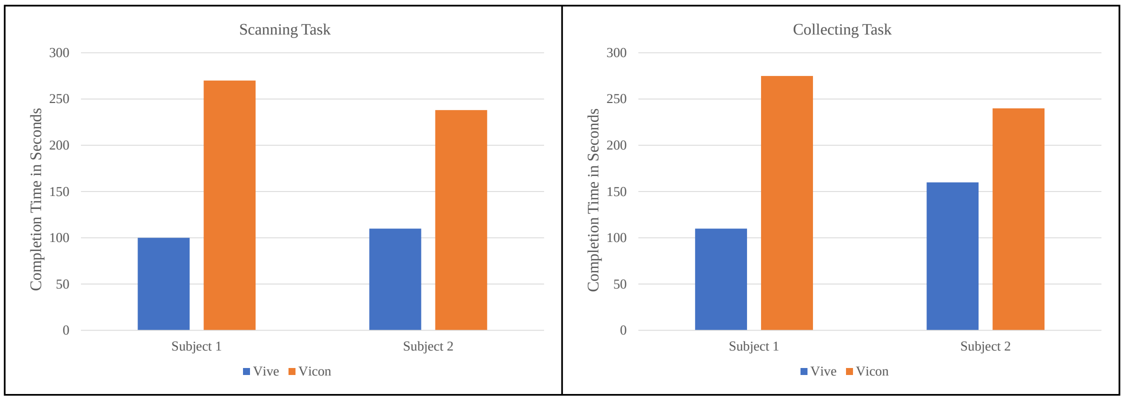

Figure 8.3: The completion times of the Scanning and Collecting tasks for both the Vive and Vicon interfaces for both the subjects.

Upon comparing the task completion times for both the Vive and Vicon interfaces while teleoperating TRINA, it was observed that the Vive interface allowed the operator to complete both the scanning and collecting tasks faster. The subjects completed the scanning task using Vive interface in 100 and 110 seconds respectively while they required 270 and 238 seconds while using the Vicon interface. For the collecting task, the Vive interface allowed the subjects to complete the task in 110 and 160 seconds while the Vicon interface required 275 and 240 seconds. The shorter time indicates that the Vive interface is efficient and easier to use, as the operators could complete the task with minimal confusion or wasted motions. Since the Vive interface is designed to provide an easy way to control the robot end-effectors the time spent for grasping objects is significantly reduced. Also the ability to use the trackpad to control the robot base's motion and rotation proved to be more intuitive than the controls of the Vicon interface.

However, the results of this experiment were of only two operators who were familiar with both the interfaces. Also, each user performed the tasks only once. Thus it is not possible to confidently draw any conclusions from this data. However, it does show that the Vive interface is comparable to the Vicon interface in performance and is capable of performing all the tasks that the Vicon interface lets the teleoperator do. Thus, the Vive interface can be an equivalent interface to the Vicon interface without the need for the expensive and rigid motion capture system of the Vicon Nexus system.

8.2 Comparison of the Vive and Gamepad interfaces

The Kinova Gen3 Jaco arm can be teleoperated using the Vive interface as mentioned in **Chapter 7** and a gamepad interface (refer Fig. 8.4). The workspace of the Kinova arm is much smaller than the TRINA robot and is without the mobile base. As mentioned in Section 4.2, performing highly precise operations is another cause for fatigue. Literature has stated that interfaces designed with the joystick based devices are better suited for precise operations because of their ability to generate discrete and small motion commands [52]. Motion mapping falls short in this regard as it generates continuous motion signals and controlling the robot using this interface for small motions will be challenging. However, the Vive interface because of it's blend of motion mapping technology and joystick based technology in the form of the trackpad provides the unique opportunity to blend free-form teleoperation for gross movements and the ability to use the trackpad for the precise movements Section 7.2. To understand the usability of the Vive interface with and without the Trackpad Control Mode for precise operations, a pilot user study using the Gen3 robot arm was performed.

8.2.1 Experimental Set-up

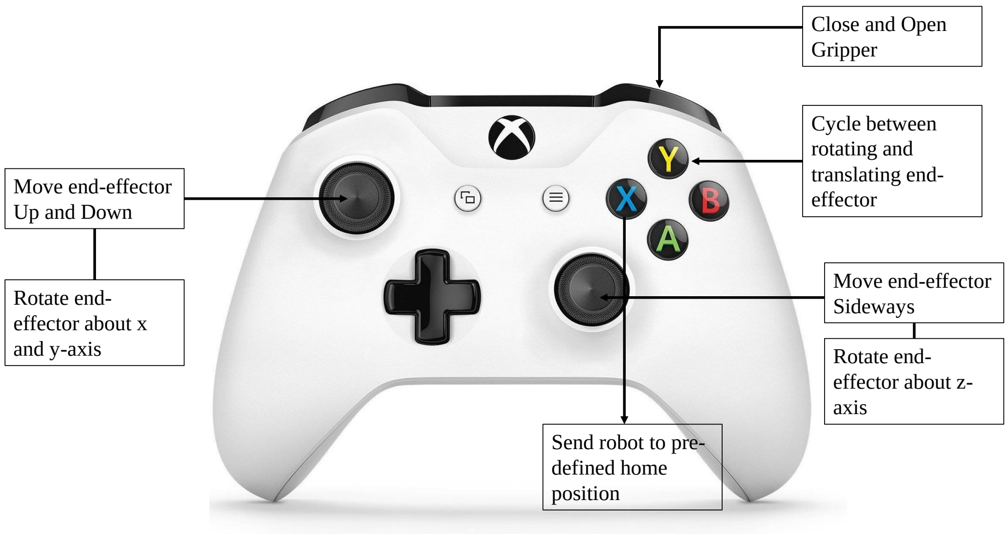

Figure 8.4: The gamepad interface used to control the Kinova robot arm.

The Vive interface for the Gen3 arm is as shown in **Chapter 7** and the gamepad interface is shown in Fig. 8.4. In order to facilitate easy and precise teloperation, a variation of the Vive interface introduced in Section 7.2 which allows the use of the trackpad to control the end-effector is also used to control the Gen3 arm. The teleoperator can look at the robot and the workspace while teleoperating the robot (refer Fig. 8.6). The operator is required to perform different tasks like picking and placing small objects scattered in the workspace and to control the end-effector orientation of the robot arm while reorienting the end-effector to read different numbered labels in the workspace.

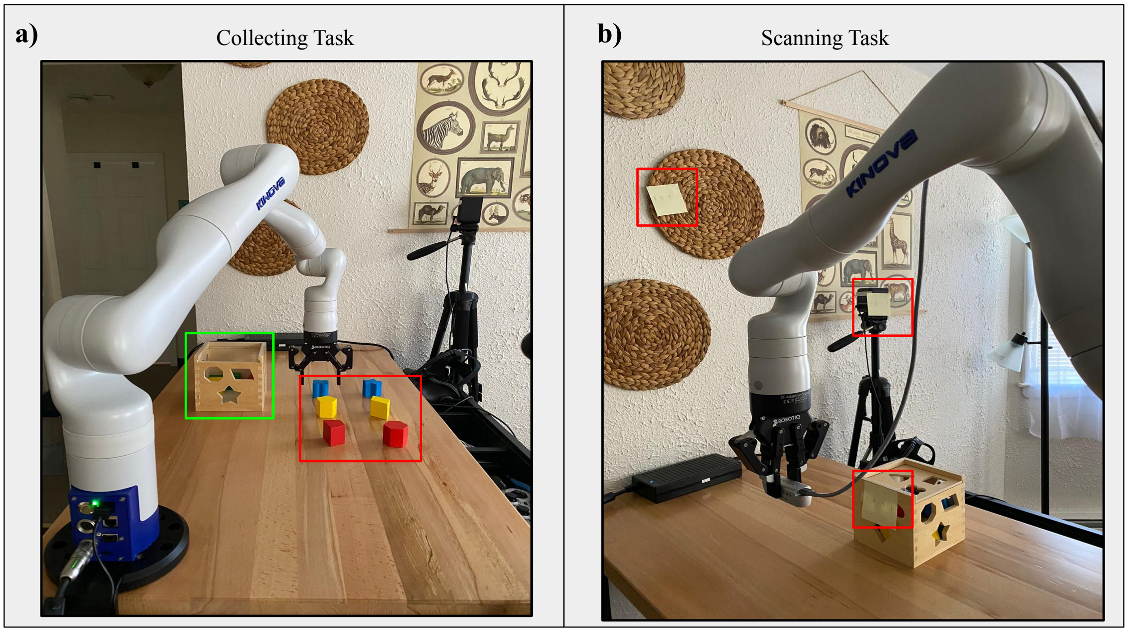

Figure 8.5: a) The collecting task involves operating the arm to transport the small objects highlighted in red to the target box highlighted in green. b) The scanning task involves manipulating the robot arm with the camera to read the numbers in the three labels highlighted in red.

8.2.2 Participants and Tasks

Participants

The pilot study invovled (N=2) participants who were involved in the development of the Vive interface and the Gamepad interface for the Kinova arm. The participants are familiar with operating the Gen3 arm using both variations of the Vive interfaces and the gamepad interface.

Tasks

The participants had to perform two tasks, namely the *collecting* and *scanning* tasks (refer Fig. 8.5). In the *collecting task*, the teleoeprator must pick up six small wooden block objects scattered on the workspace and drop them into a box using the Gen3 robot arm. This task requires free-form motion to move quickly between the box and the target objects and precise movements of the end-effector when picking up the small objects. Three trials each of this task was performed using the gamepad, Vive and the Vive with trackpad interfaces. Since the handling and manipulation of objects is the most common action a nurse performs while doing her duties, that is why this task has been designed to focus on this aspect of nursing tasks. In the *scanning* task, the teloperator must read numbered labels present in three locations of the robot workspace. The operator reads the numbers through the camera feed from a camera attached to the robot end-effector. Similar to the scanning task devised for the TRINA robot, this task too places emphasis on free-form teleoperation and orientation control of the end-effector. Again, three trials each of this task was performed using the three distinct interfaces. For both tasks, the completion time of each trial was recorded.

Figure 8.6: The operator teleoperating the Kinova arm while performing the collecting task.

8.2.3 Results and Discussion

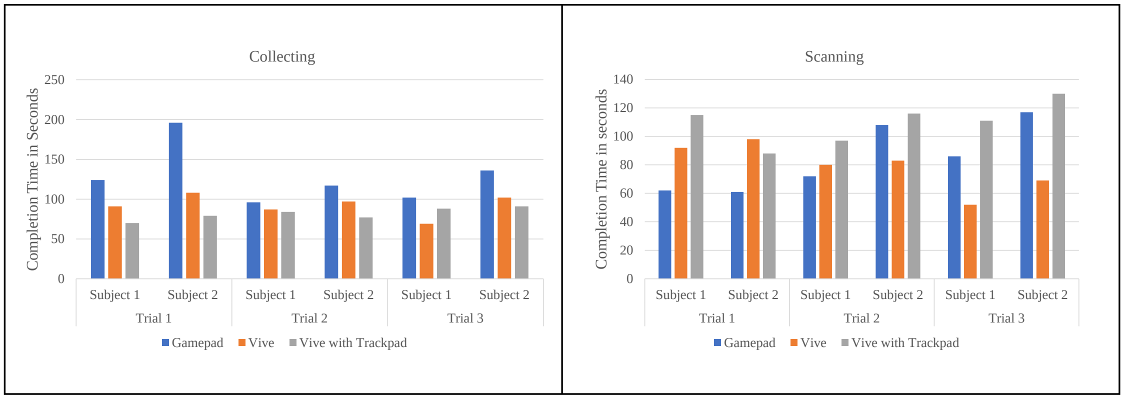

Figure 8.7: The completion times of the Collecting and Scanning tasks for both variations of the Vive interface and the gamepad interface for both the subjects.

Fig. 8.7 reports the task completion times for the individual trials of the *collecting* and *scanning* tasks for all the three interfaces. The average times for the individual tasks across all the trials and both the subjects for the *collecting* tasks are as follows: 128.5 ± 33 seconds for gamepad, 92.33 ± 12 seconds for Vive interface and 81.5 ± 7 seconds for the Vive interface with trackpad usage (refer Fig. 8.8). The shorter time for the Vive interface with the trackpad implementation suggests that using motion mapping to cover the relatively large distance from the box to the object and using the trackpad for the precise manipulation of picking up the object seems to be an effective strategy. In general, the motion mapping interface proved to be faster than the gamepad interface as it allowed the users to travel multiple degrees of freedom simultaneously more easily and intuitively.

The average times for the individual tasks across all the trials and both the subjects for the *scanning* tasks are as follows: 84.33 ± 24 seconds for gampead, 79 ± 17 seconds for the Vive interface and 109.5 ± 15 seconds for the Vive interface with the trackpad feature (refer Fig. 8.8). This task focuses on free-form manipulation and manipulating the orientation of the end-effector. As previously proven in Section 4.1, motion

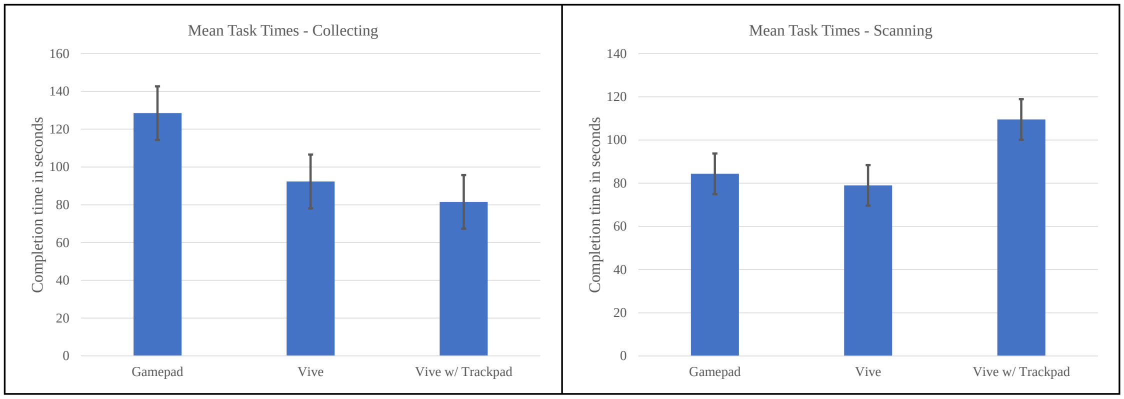

Figure 8.8: The mean task completion times across all users and trials for the Collecting and Scanning tasks for both variations of the Vive interfaces and the gamepad interface for both the subjects.

mapping has proven to be the most intuitive interface for the purpose of free-form teleoperation. This might be the reason the Vive interface shows faster time than the gamepad interface. However, the Vive interface with the trackpad is the slowest interface and the added complexity of trackpad control might have resulted in the slower time. However, as the trackpad feature is an optional the operator can chose to use this feature only when when required, maximizing the potential of the Vive controller as a teleoperation interface.

As mentioned in the results of the TRINA experiment, the vailidity of the results are limited by the number of participants. However, these results show a trend of how motion mapping can be successful for free-from teleoperation. It also shows how using the trackpad feature on the Vive controller is useful as a feature to control a robot using discrete and small motion commands. These trends and results however have to be confirmed with user studies with a larger subject pool however.

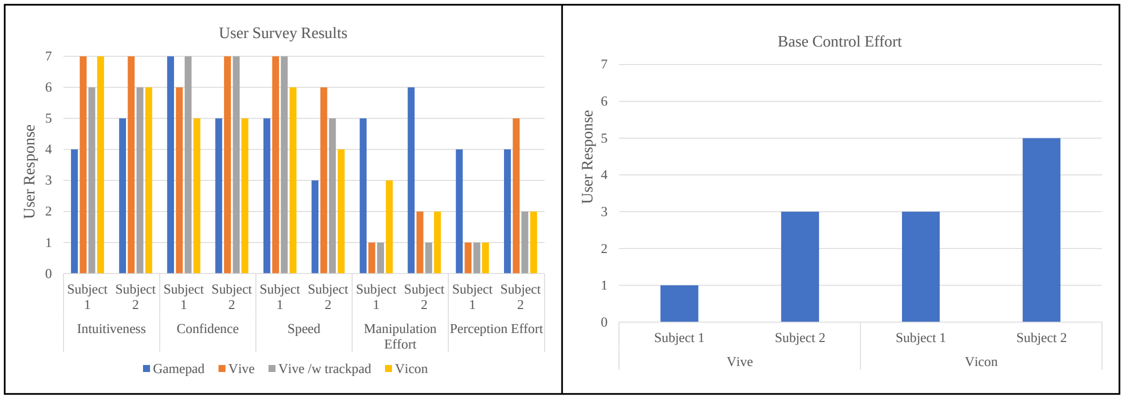

Figure 8.9: The user survey responses for their subjective feedback about the various features of the Gamepad, Vive, Vive with trackpad and Vicon interfaces. Since the base control is a feature only with the TRINA interfaces, only the Vive and Vicon interfaces were considered.

8.2.4 Survey Results

The survey results from a custom questionnaire detailing the two users' respones is presented in Fig. 8.9. Intutiveness is defined as how easy the interface was to learn and use. Confidence refers to the teleoperator's confidence in accomplishing the task while using the respective interface for teleoperation. Speed refers to how quick the interface let the operator do the task. The final two parameters denote the effort required for manipulation and perception through cameras while using the interface. The subjective effort required to control the robot base which is applicable only to the TRINA is presented in the right half of Fig. 8.9.

The survey suggests that the users finds the gamepad as the least intuitive while the Vive, Vive with trackpad and Vicon are all equally intuitive. In terms of the user's confidence in the interface performing the task the Vicon rated the least. The gamepad also fared poorly in speed, manipulation and perception effort. The Vive interfaces have also perform equally as good if not better in terms of manipulation and perception effort. The Vive interface also performs better for controlling navigation of the TRINA robot than the Vicon in the user reported survey.

8.2.5 Further User Feedback

The participants of the user's also provided their opinions on the different capabilities of the interface in terms of controllability, accuracy, efficiency, intuitiveness, effort and dexterity, the reasons for this opinion and these comments are summarized and reported below.

Gamepad

- **Controllability**: It offers most controllability as one can control even minute movements. All degrees of freedom can be individually controlled.
- **Efficiency**: It is hard to move between two points easily as multiple degrees of freedom cannot be simultaneously controlled easily or intuitively. As a result the interface is slower.
- **Accuracy**: As minute movements can be easily controlled the accuracy of this interface is very good.
- **Intuitiveness**: There are several degrees of freedom that cannot be controlled simultaneously. Very little information can be extracted from the gamepad at a given point of time. Thus, a lot of mode switches or different joysticks are to be toggled to control it correctly.
- **Effort**: Minimal physical or mental workload.
- **Dexterity**: Not very dexterous as free form teleoperation is not possible. Multiple degrees of freedom cannot be easily controlled.

Vive

- **Controllability**: The controllability of Vive is not as much as gamepad. When having to perform fine manipulations, the inability to provide discrete and small movement commands makes it harder.
- **Efficiency**: It is very efficient to move between points with limited motion commands. Grasping is also easier.
- **Accuracy**: It is great for performing large motions, but when it comes to dealing with smaller motions it becomes less accurate.
- **Intuitiveness**: Easy to learn and operate.
- **Effort**: Noticeable Physical fatigue, not as much as Vicon as grasping has become easier.
- **Dexterity**: Ability to control all degrees of motion simultaneously makes this very dexterous.

Vive with Trackpad Control Mode

- **Controllability**: The use of trackpad while performing fine manipulation makes it easier than the default Vive interface. The small motion commands provided to the robot enable more precise control.
- **Efficiency**: Same as the default Vive interface.
- **Accuracy**: Trackpad allowing minute movement commands makes it highly accurate when controlling with the trackpad. Thus, large motions can be performed with the motion mapping while finer movements can be done by the trackpad.

- **Intuitiveness**: Easy to learn and operate. However, sometimes the switching from trackpad to motion mapping adds to the complexity.
- **Effort**: Same as the default Vive interface.
- **Dexterity**: Same as the default Vive interface.

Vicon

- **Controllability**: Similar to the deafult Vive interface, it is difficult to perform fine manipulations as the control is continuous.
- **Efficiency**: Similar experience to the two Vive interfaces. However grasping is harder as several adjustments are required for a reliable grip.
- **Accuracy**: Same as the default Vive interface.
- **Intuitiveness**: Identified as the easiest to learn as direct human motion to robot.
- **Effort**: Highest physical demand.
- **Dexterity**: Same as the default Vive interface.

Chapter 9

Future Work

9.1 Comprehensive User Studies

The results from the pilot study show some trends like the Vive interface being faster than the Vicon interface for the tasks mentioned in Section 8.1.2 when teleoperating the TRINA. The results from Section 8.2.2 show that the Vive with the trackpad functionality performs faster for picking up objects while the default Vive interface performs faster for the scanning task.

The survey results also suggest that the Vive interface is intuitive to learn, easy and reliable to use when compared to the gamepad interface. The survey also implies that the precision of the Vive interface improves with the trackpad feature. The Vive interface also scored higher than the Vicon interfaces in terms of reliability and the ability to control the base while operating the TRINA.

However, these results are not conclusive enough. While they highlight certain trends in the usability of the interfaces and their performance, these studies involved only two participants and they were involved in the development of the Vive and Vicon interfaces. Conducting further user studies with a larger population (atleast N=8) and involving the nursing population to teleoperate the robots similar to the experimental studies run in Section 4.1 will help confirm the observations from the user studies presented in **Chapter 8**. As the users will be the potential end users, the results will be representative of how the target population for the interfaces will perform while teleoperating with these interfaces.

9.2 EMG Analysis

The results from Section 4.2 indicated that manipulation of objects and reaching to grasp objects was one of the most tiring actions while teleoperating using motion capture. The Vive interface was designed to prioritize grasping while teleoperation in order to make the interface more ergonomic and easy to use.

As the Vive interface tries to address the fatigue causing actions using EMG sensors to monitor the impact of this interface on reducing physical fatigue. Comparing the EMG signals from the user studies involving the Vicon and Vive mentioned in Section 9.1 will help identify the impact of the Vive interface in reducing physical fatigue.

The Vive interface with the trackpad functionality to control the linear motion of the end-effector can also potentially reduce the physical fatigue associated with the Vive interface. The major positive of using the gamepad interface is the limited physical activity attributed to teleoperating using the gamepad. By imparting this gamepad like feature to the Vive interface by using the trackpad, the overall phyhsical activity associated with the finer manipulation will be reduced if the operator uses this feature. Having user studies with EMG sensors to capture the muscle activity can confirm this hypothesis.

9.3 Improvements to the Vive Interface

The Vive interface will be further augmented with teleoperation assistance similar to the autonomous reach to grasp mechanism reported in Section 4.4.1. The detection mechanism will be replaced with an Aruco marker [163] based detection system. Thus the object's location and orientation can be determined based on the camera detecting these markers and the entire detection process becomes faster. There won't be a need for a RGB-D camera and detection system will be reliable enough to generate better automation techniques and improve the interface. The addition of haptic feedback while teleoperating to alert users of proximity to target locations or obstacles will also be implemented. This bi-directional communication between the robot and the operator will improve the trust of the operator in the interface and enhance the performance of the interface.

9.4 Integrating Head Mounted Display: Active Telepresence and Augmented Reality

The integration of the Head Mounted Display with the Vive interface enables additional impropvements to the teleoperation experience like the development of active telepresence and inclusion of augmented reality.

An operator is better able to teleoperate the robot if he can gain better situational awareness. This means that the operator must be able to get an understanding of his environment and his location in this environment. Through active perception the operator can better perceie their environment by choosing what to perceive and when and how to achieve this perception [164]. The operator can control the camera through the motion of their Head Mounted Display to achieve this active perception. The operator thus can control the cameras like how they would control their own vision for better perception of the environment. Tracking the motion of the Head Mounted Camera simultaneously with the VR handheld controllers will result in a complete teleoperation interface. If the cameras are in the wrist as presented in the experiments mentioned in Section 4.2, then the operator insted of using motion tracking of the hands can use the head movements to control their video feedback, like how they would when control their heads to control perception.

In order to improve the immersion of the experience provided by the video feedback to the Head Mounted Display, augmented reality can also be used. By displaying the real-time position of the robot end-effectors in the video stream in the Head Mounted Display or by showing the distance to potential obstacles or target objects, the operators teleoperation experience becomes more intuitive and easy. These interfaces will also be tested for their effectiveness by conducting similar user studies as mentioned in Section 9.1.

9.5 Publication Plans - Conferences and Journals

As a part of the the prior work for this thesis, the work done analyzing the different teleoperation interfaces, analyzing the physical fatigue associated with motion mapping as a teleoperation interface and optimizing the motion mapping interface through autonomous assistance has been summarized in Table 9.1.

The current design of the Vive interface along with further updates are planned to be presented at peer reviewed conferences as seen in Table 9.2.

Publication Venue	Summary
IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2019	Analyze the EMG signals recorded from teleoperators controlling the TRINA robot and identify the physical fatigue caused due to teleoperation using motion capture as a teleoperation interface. Identified objects grasping, fine manipulations and steady arm postures as causing the most physical fatigue.
IEEE International Conference on Robotics and Automation (ICRA), 2020	Introduced teleoperation assistance to automate reach to grasp operations. The EMG signals recorded during the various user studies identify reduced physical effort required for teleoperation due to the teleoperation assistance. A subjective survey of the participants also suggests that users prefer the assistance for teleoperation. This also identifies object grasping as a tedious task during teleoperation and should be focused on as the priority while designing a teleoperation interface.
ACM Transactions on Human-Robot Interactions, 2020 (Journal, in submission)	Results from user studies conducted with nursing students and registered nurses comparing Vicon, gamepad and stylus based interfaces for teleoperating TRINA suggests motion capture as the preferred form of teleoperation interface for the target end user. The journal submission also summarizes and expands upon the results from the previous conference submission from IROS, 2019 and ICRA, 2020.

Table 9.1: Peer reviewed conference papers and Journal submissions.

Publication Venue	Summary	Submission Deadline
ACM/IEEE International Conference on Human-Robot Interaction, 2021	The current design of the Vive interface will be augmented with haptic feedback. Based on the end-effector's distance from target locations and obstacles, the handheld controller will be made to vibrate, ensuring bi-directional communication between the robot and the operator. The entire design ideology and implementation will be documented in this submission.	October 5, 2020
IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2021	A more comprehensive user study involving potential end users like nursing students and registered nurses will be conducted to compare the Vive interface with Vicon interface to control the TRINA robot. This user study will look to verify the trends observed in the pilot user studies presented in this thesis. The user study will try to objectively and subjectively verify the intuitiveness, efficiency and performance of the two interfaces.	TBD (Approximately March, 2021)

Table 9.2: Planned peer reviewed conference paper submission.

Chapter 10

Broader Impact of this Research

The immediate impact of progress in this field of research will be felt in the healthcare industry. During the COVID-19 pandemic of 2020, the healthcare industry was overwhelmed by the large influx of patients. Several hospitals were understaffed and under-prepared and the quality of healthcare provided was severely affected. This compounds the pre-existing problem of nursing shortages experienced worldwide [165, 166].

Developing intuitive, ergonomic and efficient teleoperation interfaces to control humanoid mobile robots means that nurses no longer have to expose themselves to the hazardous conditions of a contagious disease ward while performing their duties. Teleoperated robots can also remove the temporal and physical barriers present between the patient and the healthcare provider. The presence of teleoperated robots in a healthcare institution means that nurses or doctors can still provide their services, even if they cannot be physically present there. Thus robot teleoperation ensures timely availability of medical attention while also addressing the issues of nurse safety and shortage of nurses.

Robot teleoperation can also make nursing education safer and easier. Instead of having the relatively inexperienced nursing students learn from video demonstrations, they can safely practice their duties via a teleoperated robot. In this way robot teleoperation can also open several interesting avenues into improving and modernizing nursing education.

The robot teleoperation also doesn't have to be limited to application in healthcare institutions. Developing intuitive teleoperation interfaces accelerates the growth of human-robot collaboration. These interfaces can be applied to industries like manufacturing, space exploration and military too.

Bibliography

[1] T.-C. Lin, A. U. Krishnan, and Z. Li, "Physical fatigue analysis of assistive robot teleoperation via whole-body motion mapping," in *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2019, pp. 2240–2245.

[2] ——, "Shared autonomous interface for reducing physical effort in robot teleoperation via human motion mapping," in *2020 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2020.

[3] Z. Li, P. Moran, Q. Dong, R. J. Shaw, and K. Hauser, "Development of a telenursing mobile manipulator for remote care-giving in quarantine areas," in *2017 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2017, pp. 3581–3586.

[4] D. K. O'Neil, "The davinci robot: Redefining the art of surgery," Mar 2018. [Online]. Available: https://macarthurmc.com/the-davinci-robot-redefining-the-art-of-surgery/

[5] I. Ekso Bionics Holdings, "Ekso bionics® receives fda clearance to market its eksonr™ robotic exoskeleton for use with acquired brain injury patients," Jun 2020. [Online]. Available: https://www.globenewswire.com/news-release/2020/06/25/2053400/0/en/Ekso-Bionics-Receives-FDA-Clearance-to-Market-its-EksoNR-Robotic-Exoskeleton-for-Use-with-Acquired-Brain-Injury-Patients.html

[6] "Paro therapeutic robot." [Online]. Available: http://www.parorobots.com/index.asp

[7] E. Ackerman, "irobot and intouch health announce rp-vita telemedicine robot," *IEEE Spectrum*, 2012.

[8] ——, "Moxi prototype from diligent robotics starts helping out in hospitals," *IEEE Spectrum. https://spectrum. ieee. org/automaton/robotics/industrial-robots/moxi-prototype-fro m-diligent-robotics-starts-helping-out-in-hospitals*, 2018.

[9] F. Lo Scalzo, "Tommy the robot nurse helps keep italy doctors safe from coronavirus." [Online]. Available: https://www.physiciansweekly.com/tommy-the-robot-nurse/

[10] T. Mukai, S. Hirano, H. Nakashima, Y. Kato, Y. Sakaida, S. Guo, and S. Hosoe, "Development of a nursing-care assistant robot riba that can lift a human in its arms," in *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems.* IEEE, 2010, pp. 5996–6001.

[11] E. Ackerman, "How diligent's robots are making a difference in texas hospitals." [Online]. Available: https://spectrum.ieee.org/automaton/robotics/medical-robots/how-diligents-robots-are-making-a-difference-in-texas-hospitals

[12] G. Yang, H. Lv, Z. Zhang, L. Yang, J. Deng, S. You, J. Du, and H. Yang, "Keep healthcare workers safe: Application of teleoperated robot in isolation ward for covid-19 prevention and control," *Chinese Journal of Mechanical Engineering*, vol. 33, no. 1, pp. 1–4, 2020.

[13] V. Annem, P. Rajendran, S. Thakar, and S. K. Gupta, "Towards remote teleoperation of a semi-autonomous mobile manipulator system in machine tending tasks," in *International Manufacturing Science and Engineering Conference*, vol. 58745. American Society of Mechanical Engineers, 2019, p. V001T02A027.

[14] Y. Zhou, M. Asselmeier, and A. LaViers, "Toward expressive multi-platform teleoperation: Laban-inspired concurrent operation of multiple joints on the rethink robotics baxter robot in static and dynamic tasks," in *Proceedings of the 6th International Conference on Movement and Computing*, 2019, pp. 1–8.

[15] B. Fang, F. Sun, H. Liu, and D. Guo, "A novel data glove using inertial and magnetic sensors for motion capture and robotic arm-hand teleoperation," *Industrial Robot: An International Journal*, 2017.

[16] C. G. Welker, V. L. Chiu, A. S. Voloshina, S. H. Collins, and A. M. Okamura, "Teleoperation of an ankle-foot prosthesis with a wrist exoskeleton," *bioRxiv*, 2020.

[17] M. Schepers, M. Giuberti, G. Bellusci *et al.*, "Xsens mvn: Consistent tracking of human motion using inertial sensing," *Xsens Technologies*, pp. 1–8, 2018.

[18] A. Hadjakos, "Pianist motion capture with the kinect depth camera," in *Proceedings of the Sound and Music Computing Conference.* Citeseer, 2012, pp. 303–310.

[19] T. Chai, "Motion capture." [Online]. Available: http://www.tonychai.com/mocap.html

[20] X. Gu, Y. Zhang, W. Sun, Y. Bian, D. Zhou, and P. O. Kristensson, "Dexmo: An inexpensive and lightweight mechanical exoskeleton for motion capture and force

feedback in vr," in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, 2016, pp. 1991–1995.

[21] "Kinova gen 3." [Online]. Available: https://www.kinovarobotics.com/en/products/gen3-robot

[22] K. Hauser and R. Shaw, "How medical robots will help treat patients in future outbreaks." [Online]. Available: https://spectrum.ieee.org/automaton/robotics/medical-robots/medical-robots-future-outbreak-response

[23] D. Tolani and N. I. Badler, "Real-time inverse kinematics of the human arm," *Presence: Teleoperators & Virtual Environments*, vol. 5, no. 4, pp. 393–401, 1996.

[24] L. Schlachta-Fairchild, S. B. Varghese, A. Deickman, and D. Castelli, "Telehealth and telenursing are live: Apn policy and practice implications," *The journal for nurse practitioners*, vol. 6, no. 2, pp. 98–106, 2010.

[25] A. Walton and B. Rogers, "Workplace hazards faced by nursing assistants in the united states: a focused literature review," *International journal of environmental research and public health*, vol. 14, no. 5, p. 544, 2017.

[26] W. H. Organization *et al.*, "Coronavirus disease 2019 (covid-19): situation report, 72," 2020.

[27] G. S. Campos, A. C. Bandeira, and S. I. Sardi, "Zika virus outbreak, bahia, brazil," *Emerging infectious diseases*, vol. 21, no. 10, p. 1885, 2015.

[28] T. P. Monath and P. F. Vasconcelos, "Yellow fever," *Journal of clinical virology*, vol. 64, pp. 160–173, 2015.

[29] S. Baize, D. Pannetier, L. Oestereich, T. Rieger, L. Koivogui, N. Magassouba, B. Soropogui, M. S. Sow, S. Keïta, H. De Clerck *et al.*, "Emergence of zaire ebola virus disease in guinea," *New England Journal of Medicine*, vol. 371, no. 15, pp. 1418–1425, 2014.

[30] S. Y. Jeong, J.-Y. Lee, S. R. Kim, M.-J. Shin, S. E. Lee, and O. S. Kim, "Development and implementation of an education program for novice infection control nurses," *Korean journal of nosocomial infection control*, vol. 21, no. 1, pp. 18–30, 2016.

[31] I. M. Aas, "Working with telemedicine: user characteristics and attitudes," *Journal of telemedicine and telecare*, vol. 6, no. 1_suppl, pp. 66–68, 2000.

[32] R. Garcia and O. Adelakun, "A conceptual framework and pilot study for examining telemedicine satisfaction research," *Journal of medical systems*, vol. 43, no. 3, p. 51, 2019.

[33] T. F. Milliken, P. T. Clements, and H. J. Tillman, "The impact of stress management on nurse productivity and retention," *Nursing Economics*, vol. 25, no. 4, 2007.

[34] B. M. Kuehn, "Global shortage of health workers, brain drain stress developing countries," *JAMA*, vol. 298, no. 16, pp. 1853–1855, 2007.

[35] B. Wilson, M. Squires, K. Widger, L. Cranley, and A. Tourangeau, "Job satisfaction among a multigenerational nursing workforce," *Journal of nursing management*, vol. 16, no. 6, pp. 716–723, 2008.

[36] P. I. Buerhaus, D. O. Staiger, and D. I. Auerbach, "Implications of an aging registered nurse workforce," *Jama*, vol. 283, no. 22, pp. 2948–2954, 2000.

[37] S. Letvak, "Retaining the older nurse," *JONA: The Journal of Nursing Administration*, vol. 32, no. 7/8, pp. 387–392, 2002.

[38] K. C. Fleming, J. M. Evans, and D. S. Chutka, "Caregiver and clinician shortages in an aging nation," in *Mayo Clinic Proceedings*, vol. 78, no. 8. Elsevier, 2003, pp. 1026–1040.

[39] D. A. Nardi and C. C. Gyurko, "The global nursing faculty shortage: Status and solutions for change," *Journal of Nursing Scholarship*, vol. 45, no. 3, pp. 317–326, 2013.

[40] P. F. Hokayem and M. W. Spong, "Bilateral teleoperation: An historical survey," *Automatica*, vol. 42, no. 12, pp. 2035–2057, 2006.

[41] P. Vermeersch, D. D. Sampsel, and C. Kleman, "Acceptability and usability of a telepresence robot for geriatric primary care: A pilot," *Geriatric Nursing*, vol. 36, no. 3, pp. 234–238, 2015.

[42] H. Ito, M. Miyagawa, Y. Kuwamura, Y. Yasuhara, T. Tanioka, and R. Locsin, "Professional nurses' attitudes towards the introduction of humanoid nursing robots (hnrs) in health care settings," *Journal of Nursing and Health Sciences*, vol. 9, pp. 73–81, 2015.

[43] M. A. Goodrich, J. W. Crandall, and E. Barakova, "Teleoperation and beyond for assistive humanoid robots," *Reviews of Human factors and ergonomics*, vol. 9, no. 1, pp. 175–226, 2013.

[44] D. Gong, Y. Wang, J. Yu, and G. Zuo, "Motion mapping from a human arm to a heterogeneous excavator-like robotic arm for intuitive teleoperation," in *2019 IEEE International Conference on Real-time Computing and Robotics (RCAR)*. IEEE, 2019, pp. 493–498.

[45] M. V. Liarokapis, P. K. Artemiadis, and K. J. Kyriakopoulos, “Functional anthropomorphism for human to robot motion mapping,” in *2012 IEEE RO-MAN: The 21st IEEE International Symposium on Robot and Human Interactive Communication*. IEEE, 2012, pp. 31–36.

[46] ——, “Mapping human to robot motion with functional anthropomorphism for teleoperation and telemanipulation with robot arm hand systems,” in *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2013, pp. 2075–2075.

[47] C. Meeker, T. Rasmussen, and M. Ciocarlie, “Intuitive hand teleoperation by novice operators using a continuous teleoperation subspace,” in *2018 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2018, pp. 1–7.

[48] M. Ferre, M. Buss, R. Aracil, C. Melchiorri, and C. Balaguer, *Advances in telerobotics*. Springer, 2007, vol. 31.

[49] M. Brown, “Exploring the magic behind the htc vive controller,” Jul 2016. [Online]. Available: https://www.vrheads.com/exposing-magic-behind-htc-vive-controller

[50] M. Borges, A. Symington, B. Coltin, T. Smith, and R. Ventura, “Htc vive: Analysis and accuracy improvement,” in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2018, pp. 2610–2615.

[51] D. C. Niehorster, L. Li, and M. Lappe, “The accuracy and precision of position and orientation tracking in the htc vive virtual reality system for scientific research,” *i-Perception*, vol. 8, no. 3, p. 2041669517708205, 2017.

[52] D. Kent, C. Saldanha, and S. Chernova, “A comparison of remote robot teleoperation interfaces for general object manipulation,” in *Proceedings of the 2017 ACM/IEEE International Conference on Human-Robot Interaction*, 2017, pp. 371–379.

[53] B. L. Hewlett and B. S. Hewlett, “Providing care and facing death: nursing during ebola outbreaks in central africa,” *Journal of Transcultural Nursing*, vol. 16, no. 4, pp. 289–297, 2005.

[54] P. L. Sagar, “Nurses leading the fight against ebola virus disease,” *Journal of Transcultural Nursing*, vol. 26, no. 3, pp. 322–326, 2015.

[55] A. Wilson and T. N. M. Nguyen, “The zika virus epidemic: public health roles for nurses,” *OJIN: The Online Journal of Issues in Nursing*, vol. 22, no. 1, 2017.

[56] K. S. Moore, “Assessing nurse practitioner knowledge of zika virus,” *The Journal for Nurse Practitioners*, vol. 12, no. 10, pp. 697–703, 2016.

[57] L. Huang, G. Lin, L. Tang, L. Yu, and Z. Zhou, "Special attention to nurses' protection during the covid-19 epidemic," 2020.

[58] D. Jackson, C. Bradbury-Jones, D. Baptiste, L. Gelling, K. Morin, S. Neville, and G. D. Smith, "Life in the pandemic: Some reflections on nursing in the context of covid-19," *Journal of clinical nursing*, 2020.

[59] I. A. Broeders and J. Ruurda, "Robotics revolutionizing surgery: the intuitive surgical "da vinci" system," *Industrial Robot: An International Journal*, 2001.

[60] J. Marescaux, J. Leroy, F. Rubino, M. Smith, M. Vix, M. Simone, and D. Mutter, "Transcontinental robot-assisted remote telesurgery: feasibility and potential applications," *Annals of surgery*, vol. 235, no. 4, p. 487, 2002.

[61] M. J. Lum, D. C. Friedman, G. Sankaranarayanan, H. King, K. Fodero, R. Leuschke, B. Hannaford, J. Rosen, and M. N. Sinanan, "The raven: Design and validation of a telesurgery system," *The International Journal of Robotics Research*, vol. 28, no. 9, pp. 1183–1197, 2009.

[62] J. Rosen, J. D. Brown, L. Chang, M. Barreca, M. Sinanan, and B. Hannaford, "The bluedragon-a system for measuring the kinematics and dynamics of minimally invasive surgical tools in-vivo," in *Proceedings 2002 IEEE International Conference on Robotics and Automation (Cat. No. 02CH37292)*, vol. 2. IEEE, 2002, pp. 1876–1881.

[63] G. R. Sutherland, P. B. McBeth, and D. F. Louw, "Neuroarm: an mr compatible robot for microsurgery," in *International congress series*, vol. 1256. Elsevier, 2003, pp. 504–508.

[64] U. Hagn, R. Konietschke, A. Tobergte, M. Nickl, S. Jörg, B. Kübler, G. Passig, M. Gröger, F. Fröhlich, U. Seibold *et al.*, "Dlr mirosurge: a versatile system for research in endoscopic telesurgery," *International journal of computer assisted radiology and surgery*, vol. 5, no. 2, pp. 183–193, 2010.

[65] L. Van Den Bedem, R. Hendrix, G. Naus, R. Van Der Aalst, P. Rosielle, H. Nijmeijer, J. Maessen, I. Broeders, and M. Steinbuch, "Sofie, a robotic system for minimally invasive surgery," in *Proceedings of the 6th International MIRA Congress, 11-13 May 2011, Athens, Greece*, 2011, p. P056.

[66] M. M. Jhaveri, R. Benjamin-Garner, N. Rianon, M. Sherer, G. Francisco, F. Vahidy, K. Kobayashi, M. Gaber, P. Shoemake, K. Vu *et al.*, "Telemedicine-guided education on secondary stroke and fall prevention following inpatient rehabilitation for texas patients with stroke and their caregivers: a feasibility pilot study," *BMJ open*, vol. 7, no. 9, p. e017340, 2017.

[67] M. D. Galea, "Telemedicine in rehabilitation," *Physical Medicine and Rehabilitation Clinics*, vol. 30, no. 2, pp. 473–483, 2019.

[68] F. S. Sarfo, U. Ulasavets, O. K. Opare-Sem, and B. Ovbiagele, "Tele-rehabilitation after stroke: an updated systematic review of the literature," *Journal of Stroke and Cerebrovascular Diseases*, vol. 27, no. 9, pp. 2306–2318, 2018.

[69] S. N. Housley, K. Fitzgerald, and A. J. Butler, "Telerehabilitation robotics: Overview of approaches and clinical outcomes," in *Rehabilitation Robotics*. Elsevier, 2018, pp. 333–346.

[70] N. Koceska, S. Koceski, P. Beomonte Zobel, V. Trajkovik, and N. Garcia, "A telemedicine robot system for assisted and independent living," *Sensors*, vol. 19, no. 4, p. 834, 2019.

[71] M. Mariappan, V. Ramu, T. Ganesan, B. Khoo, and K. Vellian, "A remote navigation methodology for a four wheel rectangular configured holonomic mobile telemedicine robot," *IPCBEE vol*, vol. 11, 2011.

[72] N. Dao, X. Hai, L. Huu, T. Nam, and N. T. Thinh, "Remote healthcare for the elderly, patients by tele-presence robot," in *2019 International Conference on System Science and Engineering (ICSSE)*. IEEE, 2019, pp. 506–510.

[73] A. Garingo, P. Friedlich, T. Chavez, L. Tesoriero, S. Patil, P. Jackson, and I. Seri, ""tele-rounding" with a remotely controlled mobile robot in the neonatal intensive care unit," *Journal of Telemedicine and Telecare*, vol. 22, no. 2, pp. 132–138, 2016.

[74] S. Narasimha, K. C. Madathil, S. Agnisarman, H. Rogers, B. Welch, A. Ashok, A. Nair, and J. McElligott, "Designing telemedicine systems for geriatric patients: a review of the usability studies," *Telemedicine and e-Health*, vol. 23, no. 6, pp. 459–472, 2017.

[75] S. Koceski and N. Koceska, "Evaluation of an assistive telepresence robot for elderly healthcare," *Journal of medical systems*, vol. 40, no. 5, p. 121, 2016.

[76] N. M. Su, L. S. Liu, and A. Lazar, "Mundanely miraculous: the robot in healthcare," in *Proceedings of the 8th nordic conference on human-computer interaction: fun, fast, foundational*, 2014, pp. 391–400.

[77] A. Garingo, P. Friedlich, L. Tesoriero, S. Patil, P. Jackson, and I. Seri, "The use of mobile robotic telemedicine technology in the neonatal intensive care unit," *Journal of Perinatology*, vol. 32, no. 1, pp. 55–63, 2012.

[78] A. M. Hoffman, W. Lapcharoensap, T. Huynh, and K. Lund, "Historical perspectives: telemedicine in neonatology," *NeoReviews*, vol. 20, no. 3, pp. e113–e123, 2019.

[79] J. Höglander, J. H. Eklund, H. Eide, I. K. Holmström, and A. J. Sundler, "Registered nurses' and nurse assistants' responses to older persons' expressions of emotional needs in home care," *Journal of advanced nursing*, vol. 73, no. 12, pp. 2923–2932, 2017.

[80] Y. Zhao, T. Tanioka, R. Locsin, K. Osaka, and Y. Yasuhara, "The care robot trio "shin-gi-tai" in 2050: Transactive relations among psychiatrist, patient, and family," *Nursing robots: Robotic technology and human caring for elderly*, pp. 123–146, 2017.

[81] B. M. King and C. D. Barry, ""caring between" the nurse, the one nursed, and the healthcare robot: An interpreted nursing situation using the barry, gordon, king framework," *International Journal for Human Caring*, vol. 23, no. 2, pp. 168–177, 2019.

[82] J. Jiang, Z. Huang, B. Huo, Y. Zhang, and S. Song, "Research progress and prospect of nursing robot," *Recent Patents on Mechanical Engineering*, vol. 11, no. 1, pp. 41–57, 2018.

[83] T. Tanioka, K. Osaka, R. Locsin, Y. Yasuhara, and H. Ito, "Recommended design and direction of development for humanoid nursing robots perspective from nursing researchers," *Intelligent Control and Automation*, vol. 8, no. 2, pp. 96–110, 2017.

[84] R. C. Locsin and H. Ito, "Can humanoid nurse robots replace human nurses," *Journal of Nursing*, vol. 5, no. 1, pp. 1–6, 2018.

[85] N. Maalouf, A. Sidaoui, I. H. Elhajj, and D. Asmar, "Robotics in nursing: a scoping review," *Journal of Nursing Scholarship*, vol. 50, no. 6, pp. 590–600, 2018.

[86] J. Hu, A. Edsinger, Y.-J. Lim, N. Donaldson, M. Solano, A. Solochek, and R. Marchessault, "An advanced medical robotic system augmenting healthcare capabilities-robotic nursing assistant," in *2011 IEEE international conference on robotics and automation.* IEEE, 2011, pp. 6264–6269.

[87] K. Kraft and W. D. Smart, "Seeing is comforting: Effects of teleoperator visibility in robot-mediated health care," in *2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI).* IEEE, 2016, pp. 11–18.

[88] U. D. Robot, "Blue ocean robotics," *URL: https://blue-ocean-robotics.com/uvdisinfection (visited on 03/08/2018).*

[89] W.-L. Chang, S. Šabanovic, and L. Huber, "Observational study of naturalistic interactions with the socially assistive robot paro in a nursing home," in *The 23rd IEEE International Symposium on Robot and Human Interactive Communication.* IEEE, 2014, pp. 294–299.

[90] I. Olaronke, O. Oluwaseun, and I. Rhoda, "State of the art: a study of human-robot interaction in healthcare," *International Journal of Information Engineering and Electronic Business*, vol. 9, no. 3, p. 43, 2017.

[91] A. Song, C. Wu, D. Ni, H. Li, and H. Qin, "One-therapist to three-patient telerehabilitation robot system for the upper limb after stroke," *International Journal of Social Robotics*, vol. 8, no. 2, pp. 319–329, 2016.

[92] H. Janiszewski Goodin, "The nursing shortage in the united states of america: an integrative review of the literature," *Journal of advanced nursing*, vol. 43, no. 4, pp. 335–343, 2003.

[93] H. Yun, S. Jie, and J. Anli, "Nursing shortage in china: State, causes, and strategy," *Nursing outlook*, vol. 58, no. 3, pp. 122–128, 2010.

[94] D. Siela, K. R. Twibell, and V. Keller, "The shortage of nurses and nursing faculty: what critical care nurses can do," *AACN Advanced Critical Care*, vol. 19, no. 1, pp. 66–77, 2008.

[95] P. G. Shekelle, "Nurse–Patient Ratios as a Patient Safety Strategy: A Systematic Review," *Annals of Internal Medicine*, vol. 158, no. $5_Part_2, pp. 404 - -409, 032013. [Online]. Available : https : //doi.org/10.7326/0003 - 4819 - 158 - 5 - 201303051 - 00007$

[96] P. Carayon and A. P. Gurses, "Nursing workload and patient safety—a human factors engineering perspective," in *Patient safety and quality: An evidence-based handbook for nurses.* Agency for Healthcare Research and Quality (US), 2008.

[97] C. Propper, G. Stoye, and B. Zaranko, "The wider impacts of the coronavirus pandemic on the nhs," *Fiscal Studies*, 2020.

[98] J. Jun, S. Tucker, and B. M. Melnyk, "Clinician mental health and well-being during global healthcare crises: Evidence learned from prior epidemics for covid-19 pandemic," *Worldviews on Evidence-Based Nursing*, 2020.

[99] D. Bernal, J. Campos-Serna, A. Tobias, S. Vargas-Prada, F. G. Benavides, and C. Serra, "Work-related psychosocial risk factors and musculoskeletal disorders in hospital nurses and nursing aides: a systematic review and meta-analysis," *International journal of nursing studies*, vol. 52, no. 2, pp. 635–648, 2015.

[100] M. H. Long, V. Johnston, and F. Bogossian, "Work-related upper quadrant musculoskeletal disorders in midwives, nurses and physicians: A systematic review of risk factors and functional consequences," *Applied ergonomics*, vol. 43, no. 3, pp. 455–467, 2012.

[101] E. Asghari, I. Dianat, F. Abdollahzadeh, F. Mohammadi, P. Asghari, M. A. Jafarabadi, and H. I. Castellucci, "Musculoskeletal pain in operating room nurses: associations with quality of work life, working posture, socio-demographic and job characteristics," *International Journal of Industrial Ergonomics*, vol. 72, pp. 330–337, 2019.

[102] J. E. Gold, A. Kurowski, R. J. Gore, P. R. Team, and L. Punnett, "Knee pain in nursing home workers after implementation of a safe resident handling program," *American journal of industrial medicine*, vol. 61, no. 10, pp. 849–860, 2018.

[103] W. Wu, Y. Zhang, P. Wang, L. Zhang, G. Wang, G. Lei, Q. Xiao, X. Cao, Y. Bian, S. Xie *et al.*, "Psychological stress of medical staffs during outbreak of covid-19 and adjustment strategy," *Journal of Medical Virology*, 2020.

[104] . J. Maben 1, 2 and J. Bridges, "Covid-19: Supporting nurses' psychological and mental health," *Journal of clinical nursing*, 2020.

[105] A. Dilig-Ruiz, I. MacDonald, M. D. Varin, A. Vandyk, I. D. Graham, and J. E. Squires, "Job satisfaction among critical care nurses: A systematic review," *International journal of nursing studies*, vol. 88, pp. 123–134, 2018.

[106] S. G. Toh, E. Ang, and M. K. Devi, "Systematic review on the relationship between the nursing shortage and job satisfaction, stress and burnout levels among nurses in oncology/haematology settings," *International Journal of Evidence-Based Healthcare*, vol. 10, no. 2, pp. 126–141, 2012.

[107] D. S. Puskin, "Opportunities and challenges to telemedicine in rural america," *Journal of Medical Systems*, vol. 19, no. 1, pp. 59–67, 1995.

[108] N. M. A. Alnair, E. M. Malik, M. E. Ahmed, and I. I. M. Abu, "Training needs assessment for nurses in sennar state, sudan: Cross sectional study (1)," *Science Journal of Public Health*, vol. 7, no. 4, p. 104, 2019.

[109] M. Jong, "Impact of robotic telemedicine in a remote community in canada," in *Proceedings of the Fifth International Conference on eHealth, Telemedicine, and Social Medicine*. Citeseer, 2013, pp. 168–171.

[110] K. Hauser and R. Shaw, "How medical robots will help treat patients in future outbreaks," *IEEE Spectrum*, 2020.

[111] E. Ackerman, "Ava robotics introduces autonomous telepresence robot," *IEEE Spectrum*, 2018.

[112] ——, "Suitable tech introduces beampro 2 telepresence platform," *IEEE Spectrum*, 2018.

[113] K. Tsui, A. Norton, D. Brooks, H. Yanco, and D. Kontak, "Designing telepresence robot systems for use by people with special needs," in *Int. Symposium on Quality of Life Technologies: Intelligent Systems for Better Living*, 2011.

[114] S. F. Goran, “A second set of eyes: an introduction to tele-icu,” *Critical Care Nurse*, vol. 30, no. 4, pp. 46–55, 2010.

[115] K. Hashimoto, F. Saito, T. Yamamoto, and K. Ikeda, “A field study of the human support robot in the home environment,” in *2013 IEEE Workshop on Advanced Robotics and its Social Impacts*. IEEE, 2013, pp. 143–150.

[116] T. L. Chen and C. C. Kemp, “A direct physical interface for navigation and positioning of a robotic nursing assistant,” *Advanced Robotics*, vol. 25, no. 5, pp. 605–627, 2011.

[117] T. D. Viet, P. T. Doan, N. Hung, H. K. Kim, and S. B. Kim, “Tracking control of a three-wheeled omnidirectional mobile manipulator system with disturbance and friction,” *Journal of mechanical science and technology*, vol. 26, no. 7, pp. 2197–2211, 2012.

[118] T. Yamamoto, K. Terada, A. Ochiai, F. Saito, Y. Asahara, and K. Murase, “Development of human support robot as the research platform of a domestic mobile manipulator,” *ROBOMECH journal*, vol. 6, no. 1, p. 4, 2019.

[119] E. Ackerman, “Toyota gets back into humanoid robots with new t-hr3,” *IEEE Spectrum*, 2017.

[120] M. Panzirsch, B. Weber, L. Rubio, S. Coloma, M. Ferre, and J. Artigas, “Tele-healthcare with humanoid robots: A user study on the evaluation of force feedback effects,” in *2017 IEEE World Haptics Conference (WHC)*. IEEE, 2017, pp. 245–250.

[121] F. Falck, K. Larppichet, and P. Kormushev, “De vito: A dual-arm, high degree-of-freedom, lightweight, inexpensive, passive upper-limb exoskeleton for robot teleoperation,” in *Annual Conference Towards Autonomous Robotic Systems*. Springer, 2019, pp. 78–89.

[122] A. K. Sinha, S. K. Sahu, R. K. Bijarniya, and K. Patra, “An effective and affordable technique for human motion capturing and teleoperation of a humanoid robot using an exoskeleton,” in *2017 2nd International Conference on Man and Machine Interfacing (MAMI)*. IEEE, 2017, pp. 1–6.

[123] P. Herbin and M. Pajor, “The torque control system of exoskeleton exoarm 7-dof used in bilateral teleoperation system,” in *AIP Conference Proceedings*, vol. 2029, no. 1. AIP Publishing LLC, 2018, p. 020020.

[124] X. Chen, S. Nishikawa, K. Tanaka, R. Niiyama, and Y. Kuniyoshi, “Bilateral teleoperation system for a musculoskeletal robot arm using a musculoskeletal exoskeleton,” in *2017 IEEE International Conference on Robotics and Biomimetics (ROBIO)*. IEEE, 2017, pp. 2734–2739.

[125] C. Rognon, S. Mintchev, F. Dell'Agnola, A. Cherpillod, D. Atienza, and D. Floreano, "Flyjacket: An upper body soft exoskeleton for immersive drone control," *IEEE Robotics and Automation Letters*, vol. 3, no. 3, pp. 2362–2369, 2018.

[126] C. Li, C. Yang, P. Liang, A. Cangelosi, and J. Wan, "Development of kinect based teleoperation of nao robot," in *2016 International Conference on Advanced Robotics and Mechatronics (ICARM)*. IEEE, 2016, pp. 133–138.

[127] J. Avalos and O. E. Ramos, "Real-time teleoperation with the baxter robot and the kinect sensor," in *2017 IEEE 3rd Colombian Conference on Automatic Control (CCAC)*. IEEE, 2017, pp. 1–4.

[128] A. Handa, K. Van Wyk, W. Yang, J. Liang, Y.-W. Chao, Q. Wan, S. Birchfield, N. Ratliff, and D. Fox, "Dexpilot: Vision based teleoperation of dexterous robotic hand-arm system," *arXiv preprint arXiv:1910.03135*, 2019.

[129] S. Li, X. Ma, H. Liang, M. Görner, P. Ruppel, B. Fang, F. Sun, and J. Zhang, "Vision-based teleoperation of shadow dexterous hand using end-to-end deep neural network," in *2019 International Conference on Robotics and Automation (ICRA)*. IEEE, 2019, pp. 416–422.

[130] S. Park, Y. Jung, and J. Bae, "A tele-operation interface with a motion capture system and a haptic glove," in *2016 13th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*. IEEE, 2016, pp. 544–549.

[131] Z. Zhang, Y. Niu, Z. Yan, and S. Lin, "Real-time whole-body imitation by humanoid robots and task-oriented teleoperation using an analytical mapping method and quantitative evaluation," *Applied Sciences*, vol. 8, no. 10, p. 2005, 2018.

[132] L. Penco, N. Scianca, V. Modugno, L. Lanari, G. Oriolo, and S. Ivaldi, "A multimode teleoperation framework for humanoid loco-manipulation: An application for the icub robot," *IEEE Robotics & Automation Magazine*, vol. 26, no. 4, pp. 73–82, 2019.

[133] S. Fani, S. Ciotti, M. G. Catalano, G. Grioli, A. Tognetti, G. Valenza, A. Ajoudani, and M. Bianchi, "Simplifying telerobotics: wearability and teleimpedance improves human-robot interactions in teleoperation," *IEEE Robotics & Automation Magazine*, vol. 25, no. 1, pp. 77–88, 2018.

[134] J. Koenemann, F. Burget, and M. Bennewitz, "Real-time imitation of human whole-body motions by humanoids," in *2014 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2014, pp. 2806–2812.

[135] L. Fritsche, F. Unverzag, J. Peters, and R. Calandra, "First-person tele-operation of a humanoid robot," in *2015 IEEE-RAS 15th International Conference on Humanoid Robots (Humanoids)*. IEEE, 2015, pp. 997–1002.

[136] G. Du, P. Zhang, and X. Liu, “Markerless human-manipulator interface using leap motion with interval kalman filter and improved particle filter,” *IEEE Transactions on Industrial Informatics*, vol. 12, no. 2, pp. 694–704, 2016.

[137] O. Porges, M. Connan, B. Henze, A. Gigli, C. Castellini, and M. A. Roa, “A wearable, ultralight interface for bimanual teleoperation of a compliant, whole-body-controlled humanoid robot,” in *Proceedings of ICRA-International Conference on Robotics and Automation*, 2019.

[138] E. Rosen, D. Whitney, E. Phillips, G. Chien, J. Tompkin, G. Konidaris, and S. Tellex, “Communicating and controlling robot arm motion intent through mixed-reality head-mounted displays,” *The International Journal of Robotics Research*, vol. 38, no. 12-13, pp. 1513–1526, 2019.

[139] J. Liu and Y. Zhang, “Mapping human hand motion to dexterous robotic hand,” in *2007 IEEE International Conference on Robotics and Biomimetics (ROBIO)*. IEEE, 2007, pp. 829–834.

[140] K. Fischer, F. Kirstein, L. C. Jensen, N. Krüger, K. Kukliński, M. V. aus der Wieschen, and T. R. Savarimuthu, “A comparison of types of robot control for programming by demonstration,” in *2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. IEEE, 2016, pp. 213–220.

[141] K. Yokoi, K. Nakashima, M. Kobayashi, H. Mihune, H. Hasunuma, Y. Yanagihara, T. Ueno, T. Gokyuu, and K. Endou, “A tele-operated humanoid operator,” *The International Journal of Robotics Research*, vol. 25, no. 5-6, pp. 593–602, 2006.

[142] Y. Ishiguro, K. Kojima, F. Sugai, S. Nozawa, Y. Kakiuchi, K. Okada, and M. Inaba, “High speed whole body dynamic motion experiment with real time master-slave humanoid robot system,” in *2018 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2018, pp. 1–7.

[143] J. Oh, I. Lee, H. Jeong, and J.-H. Oh, “Real-time humanoid whole-body remote control framework for imitating human motion based on kinematic mapping and motion constraints,” *Advanced Robotics*, vol. 33, no. 6, pp. 293–305, 2019.

[144] J. Oh, O. Sim, H. Jeong, and J.-H. Oh, “Humanoid whole-body remote-control framework with delayed reference generator for imitating human motion,” *Mechatronics*, vol. 62, p. 102253, 2019.

[145] R. Elbasiony and W. Gomaa, “Humanoids skill learning based on real-time human motion imitation using kinect,” *Intelligent Service Robotics*, vol. 11, no. 2, pp. 149–169, 2018.

[146] E.-J. Rolley-Parnell, D. Kanoulas, A. Laurenzi, B. Delhaisse, L. Rozo, D. G. Caldwell, and N. G. Tsagarakis, “Bi-manual articulated robot teleoperation using an external rgb-d

range sensor," in *2018 15th International Conference on Control, Automation, Robotics and Vision (ICARCV)*. IEEE, 2018, pp. 298–304.

[147] L. Penco, B. Clément, V. Modugno, E. M. Hoffman, G. Nava, D. Pucci, N. G. Tsagarakis, J.-B. Mouret, and S. Ivaldi, "Robust real-time whole-body motion retargeting from human to humanoid," in *2018 IEEE-RAS 18th International Conference on Humanoid Robots (Humanoids)*. IEEE, 2018, pp. 425–432.

[148] B. Carse, B. Meadows, R. Bowers, and P. Rowe, "Affordable clinical gait analysis: An assessment of the marker tracking accuracy of a new low-cost optical 3d motion analysis system," *Physiotherapy*, vol. 99, no. 4, pp. 347–351, 2013.

[149] F. Schlagenhauf, S. Sreeram, and W. Singhose, "Comparison of kinect and vicon motion capture of upper-body joint angle tracking," in *2018 IEEE 14th International Conference on Control and Automation (ICCA)*. IEEE, 2018, pp. 674–679.

[150] J. Racko, P. Brida, A. Perttula, J. Parviainen, and J. Collin, "Pedestrian dead reckoning with particle filter for handheld smartphone," in *2016 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*. IEEE, 2016, pp. 1–7.

[151] Z. Zhang, "Microsoft kinect sensor and its effect," *IEEE multimedia*, vol. 19, no. 2, pp. 4–10, 2012.

[152] "Vive now shipping immediately from htc, retail partners expand demo locations." [Online]. Available: https://www.htc.com/us/newsroom/2016-06-07/

[153] D. Whitney, E. Rosen, D. Ullman, E. Phillips, and S. Tellex, "Ros reality: A virtual reality framework using consumer-grade hardware for ros-enabled robots," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2018, pp. 1–9.

[154] D. Whitney, E. Rosen, E. Phillips, G. Konidaris, and S. Tellex, "Comparing robot grasping teleoperation across desktop and virtual reality with ros reality," in *Robotics Research*. Springer, 2020, pp. 335–350.

[155] N. Zaman, A. Tavakkoli, and C. Papachristos, "Tele-robotics via an efficient immersive virtual reality architecture," EasyChair, Tech. Rep., 2020.

[156] A. Kristoffersson, S. Coradeschi, A. Loutfi, and K. Severinson-Eklundh, "An exploratory study of health professionals' attitudes about robotic telepresence technology," *Journal of Technology in Human Services*, vol. 29, no. 4, pp. 263–283, 2011.

[157] K. He, G. Gkioxari, P. Dollár, and R. Girshick, "Mask r-cnn," in *Proceedings of the IEEE international conference on computer vision*, 2017, pp. 2961–2969.

[158] W. Abdulla, "Mask r-cnn for object detection and instance segmentation on keras and tensorflow," https://github.com/matterport/Mask$_RCNN$, 2017.

[159] "Kinova robotics: Ros kortex," https://github.com/Kinovarobotics/ros_kortex,.

[160] Stanford Artificial Intelligence Laboratory et al., "Robotic operating system." [Online]. Available: https://www.ros.org

[161] "geometry_msgs/transformstamped message." [Online]. Available: http://docs.ros.org/melodic/api/geometry_msgs/html/msg/TransformStamped.html

[162] "sensor_msgs/joy message." [Online]. Available: http://docs.ros.org/melodic/api/sensor_msgs/html/msg/Joy.html

[163] "Detection of aruco markers." [Online]. Available: https://docs.opencv.org/trunk/d5/dae/tutorial_aruco_detection.html

[164] R. Bajcsy, Y. Aloimonos, and J. K. Tsotsos, "Revisiting active perception," *Autonomous Robots*, vol. 42, no. 2, pp. 177–196, 2018.

[165] K. Ackerson and K. A. Stiles, "Value of nurse residency programs in retaining new graduate nurses and their potential effect on the nursing shortage," *The Journal of Continuing Education in Nursing*, vol. 49, no. 6, pp. 282–288, 2018.

[166] M. Marć, A. Bartosiewicz, J. Burzyńska, Z. Chmiel, and P. Januszewicz, "A nursing shortage–a prospect of global and local policies," *International nursing review*, vol. 66, no. 1, pp. 9–16, 2019.