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14. ABSTRACT

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RPPR Final Report
as of 31-Jan-2023

Agency Code: 21XD

Proposal Number: 70984NC **Agreement Number: W911NF-17-1-0299**

INVESTIGATOR(S):

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DUNS Number: 800188161 EIN: 751305566
Report Date: 31-Mar-2022 Date Received: 30-Jan-2023
Final Report for Period Beginning 20-Jun-2017 and Ending 31-Dec-2021
Title: Robustness Studies in 3D Camera Data
Begin Performance Period: 20-Jun-2017 **End Performance Period:** 31-Dec-2021
Report Term: 0-Other
Submitted By: Gopal Gupta Email: gupta@utdallas.edu
Phone: (000) 000-0000
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STEM Degrees: **STEM Participants:** 7

Major Goals: Our main aim is the iterative development of Robust 3D (R3D) framework creating more sophisticated attacks to tamper the 3D camera data and improving the forensic techniques to detect such attacks. Towards this end, we will: (a)Design an anti-forensic framework that will carry out attacks on the 3D camera data stream by using different techniques as appropriate for the nature of the generated 3D data; (b)Next, use existing digital forensic techniques to analyze the manipulated 3D camera data stream and authenticate the data validity. The R3D framework comprises •Anti-forensic 3D object stream manipulation framework: to capture and manipulate or attack 3D data streams to generate fake streams in such a way that it is difficult to detect the manipulations. This anti-forensic framework uses different techniques depending on the type of 3D camera. For data generated by LiDAR cameras, R3D introduces attacks such as additive (copy-paste, etc) and subtractive forgeries. For RGB-D streams, R3D can use a forgery skeleton sequence from a
different source as inputs. The forged skeleton sequence can come from another live/recorded stream or one created using animation software, such as the Autodesk Motionbuilder. The system then produces a real-time realistic sequence of 3D models, like a 3D reconstruction system, would, but with the actor in the live stream performing actions shown by the forged skeleton sequence. This anti-forensic framework can also introduce human (s) into a scene where there were no humans. Forensic Framework: can analyze the 3D camera data streams and determine the possibilities for forgeries. This framework also uses techniques that vary with the type of camera. For LiDAR cameras, it uses techniques such as density consistency analyses. For RGB-D data streams, it uses approaches such as block-based depth noise evaluation to detect manipulations in the depth stream.

Accomplishments: 1. We carried out an exhaustive survey of Augmented and Mixed Reality-based measurement methodologies. These methodologies are used in serious applications for measurements in real-life situations, e.g., distance to a target. This work has been published in:

“Augmented Reality and Mixed Reality Measurement Under Different Environments: A Survey on Head-Mounted Devices”, H-J. Guo, J.Z. Bakdash, L.R. Marusich, and B. Prabhakaran, IEEE Transactions on Instrumentation & Measurement, Vol. 71, 2022. DOI: 10.1109/TIM.2022.3218303

2. A virtual environment was created to explore learning about plants. The outcome of this research was published in:
"An Augmented Virtuality System Facilitating Learning Through Nature Walk", S. Vellingiri, R. P. McMahan, V. Johnson and B. Prabhakaran, Multimedia Tools and Applications, Springer, 2022, https://doi.org/10.1007/s11042-022-13379-w.

3. Manipulating 3D data was the focus of this proposal. Through this objective, we also studied the positive benefits of such 3D manipulations. The paper below explored the benefits of creating an illusionary limb for amputees in mixed reality environments, called the mixed reality-based mirror therapy:
“Clinical Feasibility and Preliminary Outcomes of a Novel Mixed Reality System to Manage Phantom Pain: A Pilot Study”, T.M. Annaswamy; K. Bahirat, G. Raval, Y.Y Chung, T. Pham, and B. Prabhakaran, Pilot and Feasibility Studies, 8, 232 (2022), Springer. https://doi.org/10.1186/s40814-022-01187-w

4. Other related accomplishments:
Following research were outcomes of related research. In [a], we studied a virtual reality-based remote physical exam, which could be very used in non-contact scenarios such as a pandemic. In [b], we used explainaility-based metrics for selecting high quality data that can be used for training deep-learning models.
a. "Virtepex: Virtual Remote Tele-Physical Examination System", N. Khargonkar, K. Desai, B. Prabhakaran, and T. Annaswamy, Proceedings of ACM Designing Interactive Systems (DIS’22), June 2022.
b. “Core-set Selection Using Metrics-based Explanations (CSUME) for multiclass ECG”, Sagnik Dakshit, B. M. Maweu, Sristi Dakshit, B. Prabhakaran, Proceedings for IEEE (International Conference on Health Informatics) ICHI 2022, June 2022.

Training Opportunities: 7 Ph.D. students were trained in 3D forensics and mixed reality research. They have been trained in forensic techniques, analyzing RGB stereo video and LiDAR data, and building collaborative mixed reality environments. 2 of these students have defended their PhD proposal in the areas of mixed-reality and deep-learning explainability, and are expected to defend their dissertation soon (depending on they getting jobs soon).

Results Dissemination: 1. “Design of calibration module for a home-based immersive game using camera motion capture system”, Y-Y. Chung, T.M. Annaswamy, and B. Prabhakaran, Proceedings of ACM Spatial User Interactions (SUI), December 2022. (Poster Paper).
2. “Dynamic X-Ray Vision in Mixed Reality”, H-J. Guo, J.Z. Bakdash, L.R. Marusich, and B. Prabhakaran, Preoceedings of ACM Virtual Reality Software and Technology (VRST), November 2022. (Demo paper).
3. "Virtepex: Virtual Remote Tele-Physical Examination System", N. Khargonkar, K. Desai, B. Prabhakaran, and T. Annaswamy, Proceedings of ACM Designing Interactive Systems (DIS’22), June 2022.
4. “Core-set Selection Using Metrics-based Explanations (CSUME) for multiclass ECG”, Sagnik Dakshit, B. M. Maweu, Sristi Dakshit, B. Prabhakaran, Proceedings for IEEE (International Conference on Health Informatics) ICHI 2022, June 2022.
5. “Clinical Feasibility and Preliminary Outcomes of a Novel Mixed Reality System to Manage Phantom Pain: A Pilot Study”, T.M. Annaswamy; K. Bahirat, G. Raval, Y.Y Chung, T. Pham, and B. Prabhakaran, Pilot and Feasibility Studies, 8, 232 (2022), Springer. https://doi.org/10.1186/s40814-022-01187-w
6. “Augmented Reality and Mixed Reality Measurement Under Different Environments: A Survey on Head-Mounted Devices”, H-J. Guo, J.Z. Bakdash, L.R. Marusich, and B. Prabhakaran, IEEE Transactions on Instrumentation & Measurement, Vol. 71, 2022. DOI: 10.1109/TIM.2022.3218303
7. "An Augmented Virtuality System Facilitating Learning Through Nature Walk", S. Vellingiri, R. P. McMahan, V. Johnson and B. Prabhakaran, Multimedia Tools and Applications, Springer, 2022, https://doi.org/10.1007/s11042-022-13379-w.

Honors and Awards: Researcher, Balakrishnan Prabhakaran, working on this project has been appointed as IEEE MultiMedia Editor-in-Chief. He will also serve as a General Co-Chair of ACM Multimedia 2024 conference in Australia.

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)
Participant: Yu-Yen Chung
Person Months Worked: 8.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
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Person Months Worked: 5.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
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Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Somayeh Mohammadpour
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
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Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: PD/PI
Participant: Gopal Gupta
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Faculty
Participant: Balakrisnan Prabhakaran
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Robotics and Autonomous Systems (Elsevier Publications)
Publication Identifier Type: DOI Publication Identifier: https://doi.org/10.1016/j.robot.2020.103536
Volume: Issue: First Page #:
Date Submitted: 10/7/20 12:00AM Date Published: 4/15/20 5:00AM
Publication Location:
Article Title: A wearable sensor vest for social humanoid robots with GPGPU, IoT, and modular software architecture
Authors: Mohsen Jafarzadeh, Stephen Brooks, Shimeng Yu, Balakrishnan Prabhakaran, and Yonas Tadesse
Keywords: Social robotInternet of ThingsGPGPUHuman robot interactionSoftware architectureSenor vest
Abstract: Currently, most social robots interact with their surroundings or humans through sensors that are integral parts of the robots, which limits the usability of the sensors, human–robot interaction, and interchangeability. A wearable sensor garment that fits many robots is needed in many applications. This article presents an affordable wearable sensor vest, and an open-source software architecture with the Internet of Things (IoT) for social humanoid robots. The vest consists of touch, temperature, gesture, distance, vision sensors, and a wireless communication module. The IoT feature allows the robot to interact with humans locally and over the Internet. The designed architecture works for any social robot that has a general purpose graphics processing unit (GPGPU), I2C/SPI buses, Internet connection, and the Robotics Operating System (ROS). The modular design of this architecture enables developers to easily add/remove/update complex behaviors.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: ACM Transactions on Multimedia Computing, Communication, and Application
Publication Identifier Type: DOI Publication Identifier: https://doi.org/10.1145/3377353
Volume: 16 Issue: 2 First Page #: 40:1
Date Submitted: 10/7/20 12:00AM Date Published: 5/1/20 5:00AM
Publication Location:
Article Title: SCeVE: A Component-based Framework to Author Mixed Reality Tours
Authors: S. Vellingiri, R.P. McMahan, and B. Prabhakaran
Keywords: Authoring, virtual reality, mixed reality, trave, gesture-based, non-natural, framework, components, services, case study, modeling, user experience
Abstract: Authoring a collaborative, interactive Mixed Reality (MR) tour requires flexible design and development of various software modules for tasks such as managing geographically distributed participants, adaptable travel and virtual camera techniques, data logging for assessment of the incorporated techniques, as well as for evaluating the Quality of Experiences (QoE). In most cases, authors might have to develop all these software modules, instead of focusing only on the virtual environment design. In this article, we propose SCeVE, a component-based framework that supports flexible design and authoring of interactive MR tours by offering ease of access to four major design choices: (i) Synchronization, (ii) Collaborative exploration, (iii) Visualization, and (iv) Evaluation.
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Journal: ACM Transactions on Cyberphysical Systems (TCPS)
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Volume: 3 Issue: 3 First Page #: 34:1
Date Submitted: 10/7/20 12:00AM Date Published: 8/31/19 5:00AM
Publication Location:
Article Title: Improving the Security of Visual Challenges
Authors: Junia Valente, Kanchan Bahirat, Kelly Venechanos, Alvaro A. Cardenas, B. Prabhakaran
Keywords: Security of the Internet of Things (IoT), multimedia security, visual challenges, video forensics
Abstract: This article proposes new tools to detect the tampering of video feeds from surveillance cameras. Our proposal illustrates the unique cyber-physical properties that sensor devices can leverage for their cyber-security. While traditional attestation algorithms exchange digital challenges between devices authenticating each other, our work instead proposes challenges that manifest physically in the field of view of the camera (e.g., a QR code in a display). This physical (challenge) and cyber (verification) attestation mechanism can help protect systems even when the sensors (cameras) and actuators (a display, infrared LEDs, color light bulbs) are compromised.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: EEE Transactions on Instrumentation and Measurement, vol. 70, pp. 1-15, 2021, Art no. 2508715
Publication Identifier Type: Other Publication Identifier: 10.1109/TIM.2021.3077049
Volume: 70 Issue: First Page #: 1
Date Submitted: 6/26/21 12:00AM Date Published: 5/3/21 3:00PM
Publication Location: United States
Article Title: Generating Healthcare Time Series Data for Improving Diagnostic Accuracy of Deep Neural Networks
Authors: B. M. Maweu, R. Shamsuddin, S. Dakshit and B. Prabhakaran
Keywords: Deep neural networks (DNNs) , electrocardiogram (ECG) signals , electroencephalogram (EEG) signals , healthcare time series , synthetic data , time series synthesizer
Abstract: Data scarcity and class imbalance are common occurrences in healthcare datasets and have an adverse effect on classification performance of machine learning models. Artificial data generation in various applications can be used to handle these challenges. This article proposes a guided evolutionary synthesizer (GES), a tool derived from principles of genetic algorithm, and designed to generate artificial healthcare time series data for improving classification performance of machine learning models. We conducted a series of promising and confirmatory preliminary experiments performance using traditional machine learning and nonresidual convolutional neural network models to evaluate the effectiveness of GES synthetic on data classification.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Artificial Intelligence in Medicine
Publication Identifier Type: DOI Publication Identifier: https://doi.org/10.1016/j.artmed.2021.10205
Volume: 115 Issue: First Page #:
Date Submitted: 6/26/21 12:00AM Date Published: 5/3/21 5:00AM
Publication Location: United States
Article Title: CEFEs: A CNN Explainable Framework for ECG Signals
Authors: Barbara Maweu, Sagnik Dakshit, R. Shamsuddin, and B. Prabhakaran
Keywords: Deep learning, Convolution neural network, ECG Signals, Explainable AI, Explainable Framework, Synthetic healthcare data
Abstract: In the healthcare domain, trust, confidence, and functional understanding are critical for decision support systems, therefore, presenting challenges in the prevalent use of black-box deep learning (DL) models. With recent advances in deep learning methods for classification tasks, there is an increased use of deep learning in healthcare decision support systems, such as detection and classification of abnormal Electrocardiogram (ECG) signals. Domain experts seek to understand the functional mechanism of black-box models with an emphasis on understanding how these models arrive at specific classification of patient medical data. In this paper, we focus on ECG data as the healthcare data signal to be analyzed. Since ECG is a one-dimensional time-series data, we target 1D-CNN (Convolutional Neural Networks) as the candidate DL model.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Medicine and Rehabilitation Clinics (Elsevier Publications)
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Volume: 32 Issue: 2 First Page #: 437
Date Submitted: 6/26/21 12:00AM Date Published: 5/3/21 5:00AM
Publication Location: United States
Article Title: Using Biometric Technology for Telehealth and Telerehabilitation,
Authors: Thiru M Annaswamy, Gaurav N Pradhan, Keerthana Chakka, Ninad Khargonkar, Aleks Borresen, B. Pra
Keywords: Telehealth, Telerehabilitation Biometric, Pose estimation, Kinematics, Electromyography, Wearable sensors, Virtual reality
Abstract: The aim of this paper is to discuss key points in VR-based telerehabilitation exercise program in relation to an integrated analysis and evaluation of real-time electromyogram data. To achieve the stated objective, we will discuss the following key areas: 1. Creating VR-based Telerehabilitation Exercise Activities: Designing and Conducting Experiments 2. Mine association rules embedded in the EMG data streams with the associated time in telerehabilitation program and a pre-determined “dose” of VR-based exercises to predict changes in muscle function 3. Content-based similarity searching techniques such as clustering models in the collected EMG data streams to reflect similar characteristics and performance variations in exercise/balance tasks for longitudinal monitoring in telerehabilitation 4. Real-time performance evaluation/score for lower and/or upper body skeletal muscles based on EMG data streams during the telerehabilitation program.
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Date Submitted: 6/26/21 12:00AM Date Published: 4/2/21 5:00AM
Publication Location: United States
Article Title: Personalized 3D exergames for in-home rehabilitation after stroke: a pilot study
Authors: Kevin Desai, B. Prabhakaran, Nneka Ifejika, Thiru M Annaswamy
Keywords: Rehabilitation; Stroke; Computer Games; Exercise Therapy
Abstract: Purpose: To describe a novel 3-dimensional (3D) exergames system and the results of a clinical feasibility study of stroke survivors needing in-home rehabilitation. Materials and Methods: The customizable Personalized In-home eXErgames for Rehabilitation (PIXER) system captures the user's image, generates a live model, and incorporates it into a virtual exergame. PIXER provides a recording system for home exercise programs (HEPs) by adapting virtual objects, customizes the exergame and creates a digital diary. Ten persons with stroke, performed HEPs with PIXER for 1 month, and without PIXER for 2 additional months. In-game performance data, measures of physical functioning (PF) including Stroke Impact Scale (SIS), Timed Up & Go (TUG) and Goal Attainment (GA) Scale obtained at baseline, 1- and 3 months were evaluated. Results: Seventy percent of participants completed the 1-month timepoint, 50% completed all timepoints.
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CONFERENCE PAPERS:

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Conference Name: ACM Multimedia 2018
Date Received: 17-Aug-2019 Conference Date: 22-Oct-2018 Date Published: 26-Oct-2018
Conference Location: Seoul, Korea
Paper Title: ALERT: Adding a Secure Layer in Decision Support for Advanced Driver Assistance System (ADAS)
Authors: K. Bahirat, U. Shah, A. Cardenas, and B. Prabhakaran
Acknowledged Federal Support: **Y**

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Conference Name: IEEE International Conference on Multimedia and Expo (ICME) 2017
Date Received: 04-Oct-2018 Conference Date: 10-Jul-2017 Date Published: 14-Jul-2017
Conference Location: Hong Kong
Paper Title: A Study on LiDAR Data Forensics
Authors: K. Bahirat and B. Prabhakaran
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Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: ACM Multimedia 2017
Date Received: 04-Oct-2018 Conference Date: 23-Oct-2017 Date Published: 27-Oct-2017
Conference Location: Mountain View, CA, USA
Paper Title: Mr.MAPP: Mixed Reality for MAnaging Phantom Pain
Authors: K. Bahirat, T. Annaswamy, and B. Prabhakaran
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Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: ACM Multimedia, Nice, France
Date Received: 26-Jun-2021 Conference Date: 21-Oct-2019 Date Published: 21-Oct-2019
Conference Location: Nice, France
Paper Title: Using Mr. MAPP for Lower Limb Phantom Pain Management
Authors: K. Bahirat, Y-Y. Chung, T. Annaswamy, G. Raval, K. Desai, B. Prabhakaran, and M. Riegler
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Conference Name: ACM MMSys 2019
Date Received: 17-Aug-2019 Conference Date: 17-Jun-2019 Date Published: 17-Jun-2019
Conference Location: Amherst, MA, USA
Paper Title: ADD-FAR: attacked driving dataset for forensics analysis and research
Authors: Kanchan Bahirat, Nidhi Vaishnav, Sandeep Sukumaran, Balakrishnan Prabhakaran
Acknowledged Federal Support: **Y**

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Conference Name: Proceedings of 13th Workshop of the Software Engineering and Architectures for Realtime Interactive Systems, held along with IEEE VR (Virtual Reality)
Date Received: 07-Oct-2020 Conference Date: 09-Mar-2020 Date Published: 09-Mar-2020
Conference Location: Atlanta, GA, USA
Paper Title: Experience with a Trans-Pacific Collaborative Mixed Reality Plant Walk
Authors: S. Vellingiri, J. White-Swift, G. Vania, B. Dourty, S. Okamoto, N. Yamanaka, and B. Prabhakaran
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Date Received: 26-Jun-2021 Conference Date: 01-Mar-2021 Date Published: 03-Mar-2021
Conference Location: United States
Paper Title: Reinforcement Learning Framework for Navigation problems using LiDAR Scan-Based Virtual Reality
Authors: Liam J Heffernan, Briscoe Fletcher, Chris Young Jin Jung, Ammar Hasan-Mehboob Nanjiani, Marshal A
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Proceedings of IEEE Artificial Intelligence in Virtual Reality (AIVR), December 2020 (Virtual/Online Event).
Date Received: 26-Jun-2021 Conference Date: 14-Dec-2020 Date Published: 14-Dec-2020
Conference Location: United States
Paper Title: High-Quality First-Person Rendering Mixed Reality Gaming System for in Home Setting
Authors: Y-Y. Chung, H-J Guo, H.G. Kumar and B. Prabhakaran
Acknowledged Federal Support: **Y**

DISSERTATIONS:

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Institution: University of Texas at Dallas
Date Received: 07-Oct-2020 Completion Date: 3/5/20 6:00AM
Title: Assessment Of QoE And Learning Effectiveness In Collaborative Mixed Reality Environments
Authors: Shanthi, Vellingiri
Acknowledged Federal Support: **Y**

Publication Type: Thesis or Dissertation
Institution: University of Texas at Dallas
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Title: Quantifying Experience and Task Performance in 3D Serious Games
Authors: Kevin, Desai
Acknowledged Federal Support: **Y**

Publication Type: Thesis or Dissertation
Institution: University of Texas at Dallas
Date Received: 07-Oct-2020 Completion Date: 9/9/19 5:00AM
Title: Analyzing and Synthesizing Healthcare Time Series Data For Decision-Support
Authors: Rittika, Shamsuddin
Acknowledged Federal Support: **Y**

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Institution: University of Texas at Dallas
Date Received: 07-Oct-2020 Completion Date: 12/4/18 1:39AM
Title: On 3D Content Manipulation: Simplification, Modification and Authentication
Authors: Kanchan, Bahirat
Acknowledged Federal Support: **Y**

WEBSITES:

URL: https://cs.utdallas.edu/trans-paci%EF%AC%81c-mixed-reality-plant-walk/#:~:text=Reality%20Plant%20Walk-,UT%20Dallas%20Researchers%20Lead%20the%20First%2DEver%20Trans%2DPaci%EF%AC%81c,Collaborative%20Mixed%20Reality%20Plant%20Walk&text=Dr.,trans%2Dpacific%20collaborative%20plant%20walk.
Date Received: 07-Oct-2020
Title: News on Trans-Pacific Plant Walk
Description: News Item

Partners

,

I certify that the information in the report is complete and accurate:
Signature: Balakrishnan Prabhakaran
Signature Date: 1/30/23 4:01PM

Virtepex: Virtual Remote Tele-Physical Examination System

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ABSTRACT

Remote strength assessment is critical for providing accessible rehabilitation, especially in the absence of in-person meetings due to the pandemic. In this paper, we introduce "*Virtepex*", an immersive exergame for remote strength assessment developed through participatory design principles. We bring out the design process starting with a needs assessment to highlight the challenges for physicians in telehealth, followed by the expert guidelines for iterative system refinement. Virtepex addresses the challenges for remote strength assessment through a marker-less and an easy-to-setup strength estimation pipeline. It utilizes an RGB-D camera for motion tracking and an inverse dynamics module for force estimation. The force estimates are used for VR object interaction and can be assessed by a physician synchronously or asynchronously for an objective evaluation. Validation by external experts shows that Virtepex produces reliable force estimates for upper body joints, indicating the potential of marker-less force estimation for future remote assessment designs.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**; **Interactive systems and tools**.

KEYWORDS

Clinical Health, Mixed Reality, Tele-Medicine, Force Estimation, Marker-Less Method, Participatory design.

ACM Reference Format:
Ninad Khargonkar, Kevin Desai, Balakrishnan Prabhakaran, and Thiru Annaswamy. 2022. Virtepex: Virtual Remote Tele-Physical Examination System. In *Designing Interactive Systems Conference (DIS '22), June 13–17, 2022, Virtual Event, Australia.* ACM, New York, NY, USA, 14 pages. https://doi.org/10.1145/3532106.3533486

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1 INTRODUCTION

Assessing the strength in joints is a vital step in rehabilitation monitoring and general musculoskeletal examinations. In an in-person assessment, the strength of a joint is assessed using an isometric test which requires physical interaction between the physician and the patient. However, a considerable proportion of patients do not live close by to a medical center, especially in rural areas. In addition, even with such infrastructure, close interaction may be inhibited by external factors such as the COVID pandemic. Such challenges emphasize the need for tele-medicine and remote assessment procedures for ensuring continued and accessible care. There exist several approaches for remote strength assessment with sophisticated methods, in particular, (a) motion capture [52], (b) on-body sensors [11, 35] , and (c) haptic devices [51] with all three lying on one end of a spectrum, and audio-visual feedback via a video-chat application on the other end.

The sensor-based approach involves placing on-body sensors on various joints and tracking parameters of interest such as velocities, accelerations, and muscle activation. However, such an approach requires additional technical expertise in dealing with the sensors and their accurate placement on the body. Such sensors also impede natural motion and sometimes cause discomfort to users. Without the on-body sensors, other motion capture methods require specialized cameras which are calibrated across multiple viewpoints and hence cannot be readily set up in a patient's home for remote assessment. Haptics-based methods also suffer from similar challenges of expensive setup and coordination of several devices working in tandem. Additionally, most of these systems focus on a live, synchronous version of assessment via video chat interaction and are generally not conducive to an asynchronous use case which can inhibit real-world adoption. The widespread availability of cheap RGB + Depth (RGB-D) cameras offers an avenue [15, 37] for providing non-invasive tracking and enhanced levels of feedback without the hassle of calibration. RGB-D cameras utilize the depth stream to provide the inference and tracking of human joints in the absence of any markers for the body segments. Specifically, Microsoft Kinect v2 uses trained machine learning models [47] to perform pixel-level segmentation for labeling the body parts such as limbs, torso, etc. To the best of our knowledge, almost none of the prior works have utilized marker-less force estimation for designing a remote strength assessment tool. We attempt to close this research gap by presenting *Virtepex*, a system for aiding physicians in remote strength evaluation via principled feedback.

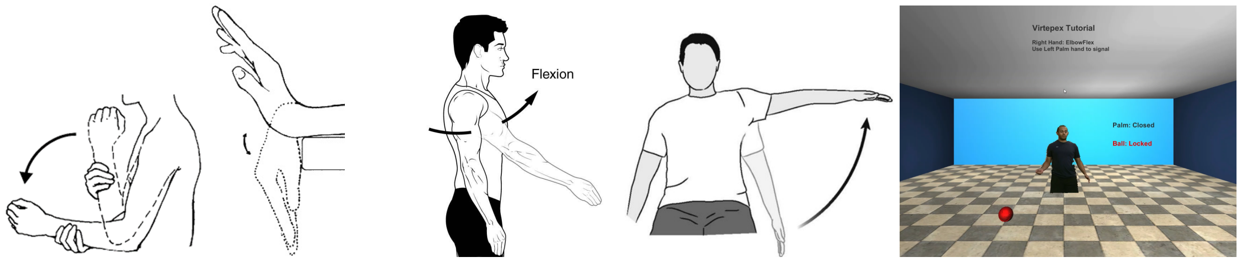


Figure 1: Four movements tracked by Virtepex and a Tutorial scene where the ball changes color on a change in a hand gesture.

1.1 Design and Evaluation Process

In this paper, we present the design and development of Virtepex as a tool for aiding marker-less assessment. We began the design with a needs assessment study which showed the gap in current methods and provided a context for the design process. Providing an interactive environment with collaborative options [18] is crucial for increased adoption as a rehabilitation tool [13, 24, 26, 32]. This motivated us to model the assessment in an exergame-like fashion. We evaluated the system by conducting experiments along two themes: a) system efficacy study from a subject matter expert (SME) side and b) overall user experience. The former tries to measure its effectiveness as a tool in providing additional knowledge to physicians about a patient's strength while the latter measures the virtual environment user experience. We recruited experts from Veterans Affairs hospital who were a mix of residents, MDs, and interns in the PM&R (Physical Medicine and Rehabilitation) department for the system efficacy study.

The results from the study indicate a strong potential in Virtepex for helping SMEs conduct remote strength assessments in a marker-less fashion. Its virtual environment and in-game interactions were well received by SMEs, and it was favored over a standard telehealth strength assessment due to objective feedback from the force estimation pipeline. The isolated evaluation for joints, range of motion information, and the ability of the system to facilitate asynchronous evaluations made it particularly attractive from a physician's perspective. In essence, the findings indicate that the SMEs valued it as a tool for enabling better remote physical assessments for home-bound patient groups.

1.2 System Overview

The system consists of two mixed reality scenes that function as exercise games and provide an interactive and engaging element to the remote assessment procedure. The primary focus was on the upper body joints due to the ease of tracking and lower possibility of noise and occlusion (unlike lower body joints such as ankles). We targeted three upper-body joints (elbow, wrist, and shoulder) with a total of four movements as seen in Figure-1. We utilize the Microsoft Kinect (v2) as the RGB-D camera for motion tracking and 3D skeleton inference. The Kinect is particularly well suited for our task due to its real-time 3D human capture capabilities. Virtepex records the range of motion for a specified joint via the Kinect skeleton data and the time required to complete the motion via tracking hand gestures. A force value is then estimated for the observed motion using an inverse dynamics solver. This value is transmitted to virtual objects inside the game environment for in-game feedback to the physician. It is important to note that the core objective of the system is to provide objective feedback in a remote assessment scenario, and not to replace an in-person strength assessment.

1.3 Contributions

- A novel system, *Virtepex*, is designed for remote strength assessment by integrating a marker-less force estimation pipeline with a virtual environment for principled feedback to physicians.
- Development of a method for facilitating asynchronous assessments for additional value over current telehealth procedures with a relatively simple system setup.
- Extensive evaluation of the system is shown with two sets of studies supporting the usefulness of the system, its usability in future deployment, and comparison with in-person and telehealth assessments.

2 RELATED WORK

2.1 Tele-Rehabilitation

Tele-rehabilitation systems [1] tackle methods for remote interaction for patient rehabilitation across medical disciplines using telecommunications technology. They have been shown to be effective for enabling remote care and assessment across clinical categories [21], and for combating service disruption due to external factors such as the COVID-19 pandemic [31]. A recent study [5] brings out the adaptations made in telehealth infrastructure for inclusive care on account of the constraints imposed by the COVID-19 pandemic. In some prior works, telehealth has also been reviewed for acting as a replacement for in-person visits for physical rehabilitation of chronic lower back pain [27, 28], as a real-time tool for musculoskeletal conditions [12] and, in an asynchronous method of delivery for rehab following knee replacement surgery [6]. Other forms of tele-rehab consider different modalities like haptics [51]. However, even with such developments, it remains a challenge in making the systems more acceptable to end-users [4, 26]. In this regard, the somewhat non-traditional, game-based [32] medium for tele-rehab seems to be promising. Another challenge to increased adoption is an often overlooked mismatch between the design process and end-user expectations [29, 33], which emphasizes the importance of involving subject matter experts in the design process.

2.2 Mixed Reality Exergames

Haptics-based systems are frequently employed in the use case of motor rehabilitation monitoring [18, 19, 51] as the rehab requires obtaining some level of force feedback from users. Another approach is to use exoskeleton technologies [23] toward rehabilitation goals. However, such systems provide an inherent difficulty in remote rehabilitation due to their complex setup and expensive equipment. Another component of an effective rehabilitation tool is increased engagement with users [32] for which the exercise-gaming or exergaming [39] approach is well suited [48]. Exergames are usually targeted towards physiotherapy applications with some examples being the at-home physio [50], Liberi exergame for children with cerebral palsy [24], and stroke rehabilitation [2, 13, 43].

The availability of consumer depth cameras such as the Kinect v2 has aided further advances in motion tracking, gesture recognition, and other computer vision problems [22] in exergame development. Such developments allow for a more natural interaction experience with an exergame system as seen in [7, 44]. They also allow for an immersive experience via virtual/mixed reality [49] which might be crucial for enabling increased adoption [14]. Some recent works target both the general exercise regime [25] and more rehabilitation-oriented objectives of stroke [43] and spinal cord injury [40].

2.3 Estimating Forces on Body Joints

A certain level of force feedback is essential for physical rehabilitation to get an idea about the forces acting in the body joints. There has been ongoing research towards obtaining force feedback on body joints through motion capture via purely visual/depth cameras like the Kinect, which is just one of the ways to do motion and human joint tracking [14]. There is evidence to support that the forces estimated through Kinect- based motion capture are consistent with force plates as seen in [15, 37, 38]. The approach in [15] uses the impulse-momentum method to calculate the ground-based reaction forces during a jump and land procedure. A similar analysis is carried out in [38] for kinematic validation of Kinect-based motion capture and estimation of sit-to-stand dynamics [37] in a subsequent paper. The thesis work of [52] compares the Kinect sensor with a Curie-Nano sensor (equipped with an inertial measurement unit), for angular velocity and acceleration measurements across a series of experiments involving the arm and head. However, the use of Kinect can also introduce other challenges like the problem of varying limb lengths and sensitivity to occlusion [41, 42]. On a related note, myography techniques like electromyography (EMG) signals can also be used to estimate muscle activation [11, 20, 35] and integrated into the development of exergame systems [16]. Such systems are quite common for obtaining high precision muscle activation for musculoskeletal examinations.

There exist several instances of research works in other healthcare domains [10] which try to address a similar problem of providing high-level but principled feedback to physicians. Usually, they aim to provide such feedback for real-world use and position themselves as a complementary tool, rather than trying to replace the physician's assessment. For example, the line of work in [8, 9] introduces an efficient user interface for radiologists as a tool. They also show the challenges in mapping a well-studied problem (image classification) to a medical use case. Future readers could similarly benefit from our work in the context of remote strength assessment. Our literature survey showed that although there exist numerous approaches for force estimation, very few prior works have addressed the use case of remote strength assessment which brings a different set of challenges. An ideal method requires scaling to several users, and its setup complexity and cost play a big factor in its real-world usability. Through the survey, we identify the potential tradeoffs in the different approaches and foresee the benefits of using a single depth camera in estimating forces [15, 37].

3 DESIGN PROCESS OVERVIEW

Virtepex is developed following participatory design principles. The design team consisted of three SMEs, with two medical students and one senior MD with a high level of expertise in Physical Medicine and Rehabilitation (PM&R). We followed an iterative model of development with subjective feedback from the SMEs guiding changes in each iteration. We began the design process with a needs assessment study for discussing the current telehealth standards, and challenges faced by physicians in assessing strength. As seen in Figure-2, this study formed the basis for our initial prototype which involved a force estimation module for approximating strength. We validated the technical implementation and established guidelines for the next iteration (alpha version) based on subjective comments from the SMEs. The next steps involved the addition of an exergame virtual environment with different scenarios and an asynchronous option for strength evaluation. This alpha version was validated by the SME team who suggested additional changes for the final iteration (before we started the extensive evaluation study outside the design team). The table in Figure-2 encapsulates the core design guidelines established during the iterative process. We go into more detail in the following section where the iterative design and feedback during each iteration are discussed in depth.

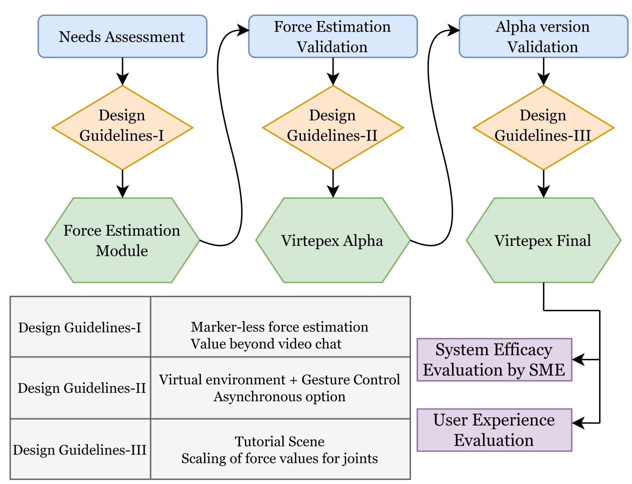


Figure 2: Overview of the Design Process and Guidelines

The diagram shown in Figure-2 can be viewed as having four layers with each layer being shaded differently. The first layer pertains to the interactions with experts who participated in the design process and gave feedback which further established the guidelines. The guidelines are the second layer in the figure and form the basis for the iterative design steps composed of three iterations (force estimation module, alpha version, and final version) shown in the third layer. In the bottom row, we show the two evaluations for the final version from an efficacy for SME and user experience perspectives. The adjoining table captures the essence of design guidelines obtained during the development of Virtepex.

4 VIRTEPEX DESIGN

4.1 Needs Assessment

We conducted a needs assessment survey in the initial stage of the design process to assess the current state of remote assessment procedures and whether they meet the needs of care providers. This had a dual purpose in motivating the development of our system and gauging the interest of physicians in its real-world adoption. The survey involved gathering responses from 25 Physical Medicine and Rehabilitation (PM&R) professionals on a 7-point Likert scale and the questions centered around the following themes:

(1) Effectiveness in assessing body joints via current Remote Assessment procedures.
(2) Accessibility of telehealth (vs in-person) and cost benefits.
(3) Engagement: whether users are willing to take up telehealth for their care.
(4) Effectiveness in reducing wait times and ease of follow-ups.

Most of the survey respondents believed that patients (87%) and colleagues (86%) are willing to use telehealth which demonstrates that users might be willing to take up novel procedures. Overall, the results suggest that the current state of telemedicine does not meet the standard needed for effective remote assessment, especially for reflexes, arm strength, and sensation. As seen in Table-1, current telehealth procedures seem to be inadequate, especially with respect to strength assessment. Additionally, an open-ended response stressed the need for "*specific joint and range of motion information*". The results from this survey, therefore, indicate the potential for a system to provide high-level feedback.

4.1.1 Design Guidelines-I. The primary objective at the beginning of the design process was to ensure a reliable and consistent (but not necessarily high precision) method to remotely evaluate the strength of a patient. A secondary objective that naturally followed was to provide additional value over standard video chat used in rehabilitation monitoring. It was necessary to avoid complex equipment setup to improve the chances of real-world adoption. In essence, the overall design centered around providing valuable, objective feedback about the observed activity from the estimated values, at least at an abstract level.

4.2 Force Estimation Module

We fulfilled the above requirements by using a depth camera (Microsoft Kinect v2) for tracking a user's joint movements. Kinect provides real-time information about the 3D human skeleton which is useful for tracking and inferring parameters such as joint positions and angles. We modeled the strength of joint via the estimating the force/torque on it when performing a specified movement. We obtained the range of motion and duration of the joint movement from a specified start and end positions and try to estimate (up to a constant), the force required to perform the observed motion. Such a modeling framework precisely fits into the inverse-dynamics formulation [30, 36] as we know about the joint's motion and want to infer the force/torque caused by the observed motion. This contrasts with the standard dynamics problem where we know the forces and have equations to predict the motion.

Table 1: Measures of central tendency for responses gathered in the needs assessment study (Section 4.1)

Category	Mean	Std. Dev
1. Remote Assessment	3.78	1.84
a) Measure Hip Range	3.34	
b) Assess arm strength	2.91	
c) Assess leg strength	3.00	
d) Assess upper extremity reflexes	1.86	
e) Assess sensation	2.82	
2. Accessibility	4.83	1.63
3. Perception/Engagement	5.25	1.18
4. Implementation/Effectiveness	4.98	1.50
5. Administrative Concerns	4.68	1.74

The core of the technical implementation involves the motion capture of the human body using Kinect and tracking the different joints and the associated angles over a time interval. Kinect does not provide the values for joint angles directly, but these values can be estimated using a vector dot product between the orientation vectors of the limb (bone) segments. The joint angles can then be used to compute kinematic quantities such as angular velocity and acceleration. Such kinematic quantities are required for the force/torque estimation through the inverse dynamics equation. Therefore, as seen in Figure-2, the focus of the initial prototype was integrating the 3D skeleton tracking with the inverse dynamics solver for the force estimation module.

4.2.1 Implementation Details. For simplicity, we modeled each upper body joint as a one-link revolute joint as all the considered movements are rotational in nature. Consequently, there was only one degree of freedom in the overall movement (angular displacement at the joint). Note that due to the simplicity of the modeling assumption, the raw force estimates were not comparable (in isolation) with the ground truth values. Nevertheless, they were consistent across movements corresponding to different strength levels, as seen in the force estimation validation experiment (Section 4.2.2). We considered three upper body joints, the elbow, shoulder, and wrist with flexion/extension movement for all of them and the abduction movement for the shoulder (see Figure-1). Additional details about the joint angle computation and the inverse dynamics algorithm are provided in Appendix A.

4.2.2 Force Estimation Validation. Experiment Design: We conducted a validation study after the initial prototype development to validate the core implementation details for the force estimation pipeline. The elbow joint's flexion movement was chosen for validation due to the lower possibility of noise in its tracked position (unlike, for example, the wrist joint). In this study, the independent variable was the observed range of motion (ROM) for the joint and the estimated force value was the dependent variable. We tested whether the estimated force values were linearly proportional to the range of motion of the joint under the previously mentioned modeling assumptions.

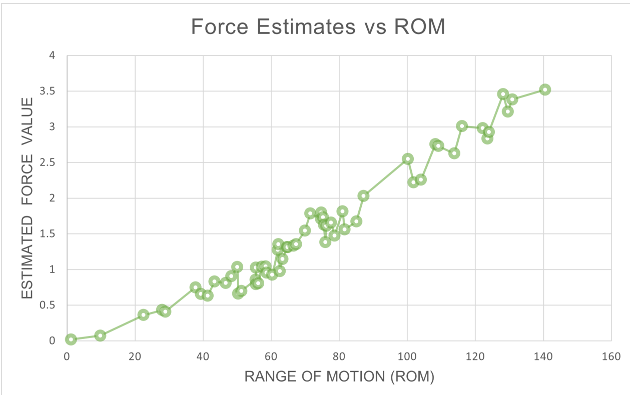


Figure 3: Linear relationship between the force estimates and range of motion for the technical validation experiment (Section 4.2.2)

Data Analysis and Results: We repeatedly performed the elbow flexion movement to gather data for the experiment. A diverse set of movements across the entire range of feasible ROM values for elbow flexion were logged. Since the time duration of the movement affects the estimates from the algorithm, care was taken to control for the time by performing the movement within a specified duration window. As we can see in Figure-3, the estimated force values were consistent with our hypotheses (their relationship with observed ROM). We can see a broad linear trend in the plot across different values for the range of motion (in degrees). Note that the minor variations from the broad linear trend potentially stem from the unobserved differences in the time duration for each movement.

4.2.3 Design Guidelines-II. We presented the initial prototype to the SMEs for a subjective evaluation and feedback after the validation of technical implementation. The prototype employed a keyboard interface that signaled the start/end of tracking and displayed the RGB video frame for the user. The SMEs noted that displaying raw force values, although informative, was not particularly effective as feedback due to the "*difficulty in interpreting the values in isolation*". Furthermore, a common challenge with in-person (or current telehealth) rehab was identified in the constraint for the patient and physician to be available at the same time (synchronous evaluation). Hence, we added a requirement of allowing for an asynchronous mode of assessment [6] to truly enable the benefits of using tele-rehab over an in-person visit. In essence, the following guidelines were obtained for the development of the next iteration:

(1) Develop an interactive environment to make the assessment session engaging and fun on account of the lack of any in-person interaction.
(2) Provide gesture-based controls for a natural interface to signal the start and end of an activity session with visual confirmation for registration of the gesture.
(3) Enable an option to play in the environment at discrete difficulty levels to aid in interpretability and standardized comparison across different users.
(4) Facilitate two-player scenarios to increase the involvement of physicians, with an asynchronous option for offline assessments.

4.3 Virtepex Alpha Version: Interactive Environment

Following feedback on the initial prototype, we modeled the user activity session (for doing the joint movements) into a simple game in a mixed reality environment to introduce an element of interactivity to the system. The game was titled *PinHit* and consisted of a scene with a bowling alley, a ball, and a single bowling pin placed in line along the alley. As the assessment targeted upper body joints, a bowling scene was suitable for modeling the virtual environment. Following works such as [25] which showed the benefits of an immersive embodiment, a live textured mesh of the user was displayed inside the game to make it more engaging to use. In PinHit, the main objective for the user is to perform the movement at their comfort level and observe whether the force estimated from their action can knock down the pin. Note that the primary objective is not to knock the pin down, but simply to perform the prescribed movement at their comfort level. When the activity is in session, the joint angle and time are tracked across each frame from the camera. At the end of the session, they are given as input to the inverse dynamics solver that estimates the force, which is then applied to the ball.

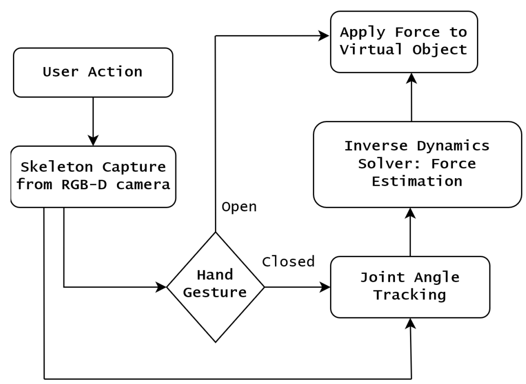


Figure 4: State Diagram of the game with Gesture Control and Force Estimation pipeline

Hand Gesture Control: We utilized the hand gesture controls provided by the Kinect to register the user's intent to start and end an activity session following some of the guidelines set in [17]. A user signals the start and end tracking of an activity (e.g., elbow flexion) by closing and opening the hand fist respectively (see Figure-4). A hand gesture control naturally corresponds to the real-world actions of holding and releasing a ball. Hence, it is the mapping used in the virtual scene. To address the potential problem of a user not knowing whether their gesture is registered, we added a simple visual cue in the scene. We toggled the color of

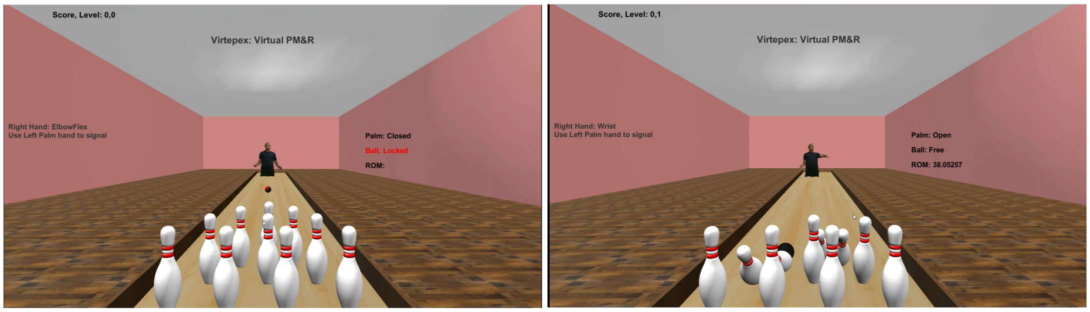


Figure 5: Single user PinHit scene during its two states described in Section 4.3

the virtual object (bowling ball) on detecting the start of an activity. Apart from the above changes, we added functionality to track three movements (wrist, shoulder flexion, and shoulder abduction) to the initial prototype.

4.3.1 Collaborative Interaction & Asynchronous Mode. The variable pin weight acted as a straightforward way to evaluate users in a standardized manner, based on their ability to knock pins from a predefined set of virtual weights. However, there was limited involvement of the physician in interacting with end-users. The interaction was restricted to simply observing the gameplay. In an ideal in-person setting, the patients test their strength against the physician, and we wanted to incorporate a similar interaction in Virtepex. To enable such an interaction, we included a collaborative option in the game to provide further motivation for rehabilitation [18, 19]. Optionally, users also got to test their strength against others in such a collaborative, two-user setting. Here the aim was to introduce a way for physicians to compare and benchmark strength against users. However, it is important to note that a competitive aspect was not desired. Furthermore, we introduced an asynchronous option to the collaborative interaction to facilitate offline rehabilitation evaluations.

An updated version of the game was developed to address the requirement of a collaborative setting between two users, and it was titled the *Midline* game. The nature of the game was changed to a two-user setting with the two instances of the game connected via a local network for the *synchronous* version. A second ball (controlled by the other player) was placed at the opposite end of the alley. This ball replaced the bowling pin from the PinHit scene. In the Midline game, both users perform the required joint movement, and motion is imparted to each ball based on their respective force estimates. The objective now becomes to overcome the opposite user's ball and cross the mid-point between the two ends. Note that the users were not asked to ensure a precise force value (through their captured actions) to overcome the opposition level. Such an interaction is closer in spirit to the nature of an in-person (isometric) strength assessment where a patient is required to exert voluntary force against a resistance provided by the physician. Depending on the physical resistance that the patient can overcome, the physician then makes a judgment about the strength of the joint on a broad scale of three to five levels.

We extended the Midline game to an asynchronous mode through a minor change in the gameplay and adding a data logging toolkit. In the asynchronous mode, users had the option of a) recording their movement for future play or b) playing against another user's recording. During the recording mode, the user performs the specified joint movement over multiple sessions, and during each session, the estimated force is logged. In the non-recording mode, the user first specifies an identifier for the opposite user. Upon entering the identifier, the game is similar to the Midline scene. The task remains unchanged: overcome the opposing ball, which has a force retrieved from the data logged from the opponent's recording. The asynchronous option also enables users to play against their previous levels or a more personalized reference level set by a physician. Therefore, the asynchronous mode of the system is a key constituent of Virtepex's ability to provide additional value over a standard telehealth visit. To summarize, all the games use the same underlying architecture: (a) use Kinect for motion tracking and hand gesture controls; (b) joint angle computation and force estimation via the inverse dynamics solver (c) application of estimated force to a virtual object inside the game and simulate physically plausible motion for feedback.

4.3.2 Alpha Version Validation. A set of four SMEs participated in a validation study for the previous iteration of Virtepex. Out of the four participants, three were from the original design team and the fourth was a senior medical student with PM&R experience. Two of the participants had a high degree of familiarity with virtual reality while the rest had little to no experience with it. The purpose of the study was to assess the interactive environment design and foresee possible difficulties in terms of system usability in a real-world setting. The feedback from the validation study consisted of two parts with the first being 7-scale Likert responses (ranging from strongly disagree to strongly agree) on questions around ease of use, equipment setup, force estimation consistency, and the second part solicited subjective comments.

Procedure: The participants were invited individually to the research lab of the first author. They were first given a brief overview of the system with details about the gesture controls and using the menu. For the evaluation, they interacted with the different game modes and tried to evaluate the strength of a person (via pre-recorded data) using the system.

Feedback: The feedback for the prototype was overall positive, with the participants being favorable to the idea of using Virtepex as an aid during remote physical assessments. The setup and use of the system were found to be easily learnable: "*The instructions do*

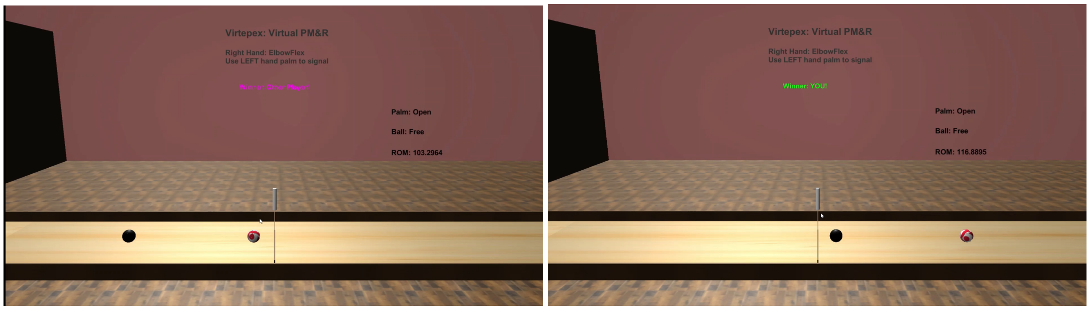


Figure 6: Async mode: The collision scenario with a midline between the two balls. The ball to cross the midline has the higher force value imparted to it and will win out in the resulting collision as described in Section 4.3.1

Table 2: Results from the alpha version validation (Section 4.3.2

Question Theme	Mean	Std. Dev
System Setup and Use	5.33	1.527
Consistent Force Feedback	5	0.816
Potential to aid remote assessment	2.91	0.5

not involve any specialized skills or knowledge of niche information" (P2). Three participants (P2, P3, P4) strongly suggested including a tutorial scene at the beginning for users to get acquainted with the procedure, for example, "*It may be helpful to have a tutorial at the start (like in many video games) to help the user understand the system.*" (P3). In terms of force feedback, a potential issue was recognized which explains a relatively lower score: "*The game felt fairly consistent when playing repeatedly for any given joint movement. However, it felt like, between different joint movements, it took different amounts of effort to move the ball*" (P3).

4.3.3 Design Guidelines-III. The results from the evaluation and qualitative feedback led to two guidelines for the final iteration of Virtepex:

(1) Develop a tutorial to help experts and users get familiar with the virtual environment and gesture control.
(2) The system should scale up the estimated force values for low-ROM joints such as the wrist joint.

4.4 Virtepex Final Version

Using the above guidelines, we made the following changes in the system before proceeding with a more extensive evaluation with external SMEs. We added a brief tutorial scene to the system startup where users could freely interact with the system and get comfortable with the gesture controls. It provided a basic level of interaction with the core elements of the system and had similar visual elements as other scenes, e.g., the change of ball color on gesture change, the display of useful information such as the joint name. We incorporated a scaling mechanism in the game mechanics for the force values imparted to the virtual ball. This was done to overcome the issue of the slow movement of the virtual ball for low total movements joints (e.g., wrist). The scaling was achieved by establishing reference ranges for ROM and force estimates (for each joint) and using them to calculate a user's relative percentage w.r.t the reference. The relative percentage determined the impulse imparted to the virtual ball. Hence, even if the detected movement was low (in absolute), there was considerable movement of the ball if the movement was close to the maximum possible movement for that joint.

5 VIRTEPEX SYSTEM EVALUATION

5.1 Experiment Setup and Hardware

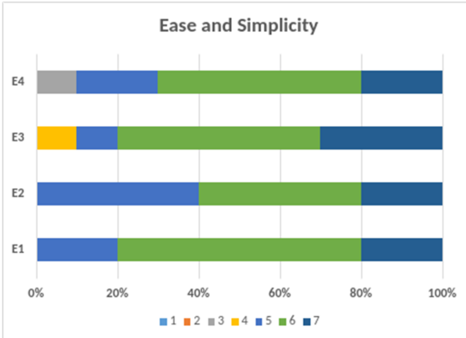
The Virtepex system requires a setup of a PC and Kinect v2 sensor directly facing the user for the motion capture. We used a PC with 32GB RAM running the Unity game engine on an Intel i7-5820K 3.3 GHz processor with Nvidia GTX 970 graphics card with 4GB memory for the experiments. The experiments were conducted in a small space (4ft x 6ft) of the research lab with adequate lighting. The small space was not a hindrance since we only considered upper-body joints with no apparent occlusion to the camera.

5.2 Evaluation: System Efficacy by SMEs

We evaluated the system by conducting experiments to measure its effectiveness as a value addition tool in providing information to physicians about a patient's strength during a remote assessment. The evaluation centered around feedback from expert participants around three broad themes:

(1) Ease and Simplicity: look and feel, ease of use, and learnability of conducting assessments via Virtepex.
(2) Quality of Experience for SMEs: responsiveness, helpfulness of the virtual assessment, and completeness of Virtepex w.r.t strength information.
(3) Comparison of Virtepex with in-person and telehealth assessments on engagement with patients, ease of obtaining strength data, and potential to replace the current standard in either case.

5.2.1 Participants. Ten subject matter experts (five male, five female) associated with the Physical Medicine and Rehabilitation (PM&R) department of Veterans Affairs hospital participated in the evaluation study with an age range from 28-55 years. This set of participants had no overlap with the team for the design process. The SME group consisted of attending interns, physical therapists,



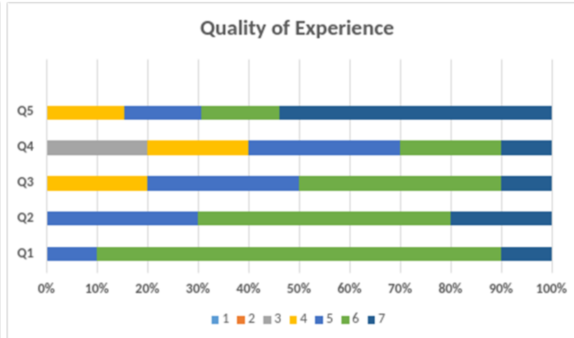


Figure 7: Stacked bar charts for Ease and Simplicity and QoE (higher score colors indicates better result) for the system efficacy study for SMEs (Section 5.2)

and MDs who had experience with conducting in-person and telehealth evaluations. Three of the participants had some degree of familiarity with VR (Virtual Reality) while others did not have much experience with it.

5.2.2 Study Procedure. The study was conducted in the presence of two medical students and a technical expert who developed the system. On average, each session with a participant took about 30-45 minutes. To begin with, participants arrived in the study room and filled out forms on demographic questions and consent. Next, a high-level overview of the system was presented to the participants with details about the motion capture and how to interact with the virtual environment. We familiarized the participants with the system and gesture controls via the tutorial scene. After completing the tutorial scene, they were instructed to play the PinHit and Midline games across all four joint movements. Although the design of the system does not foresee an evaluator utilizing the PinHit game, it was included in the study for participants' familiarity with the bowling analogy and the force estimates application to the virtual bowling ball. Finally, they also played the asynchronous version of the Midline game with multiple trials. In the asynchronous mode, they tested the strength of pre-recorded data points to get a feel for how evaluation with Virtepex might look.

The pre-recorded data points consisted of force recordings of a healthy person for all four joint movements. Data for each joint movement was recorded across four additional levels of impedance by performing the movement with dumbbell weights: 0, 2, 5, 10lbs with 0 lbs. denoting no dumbbell in hand. The multiple dumbbell weight option was motivated by current telehealth procedures where a patient might be instructed to lift different weights. For example, the patient could be asked to identify three objects – light, medium, and a heavy weight relative to their strength. The evaluator will also do the same and both will complete the motion with all three weights.

Each trial consisted of a joint, dumbbell weight combination that the participant picked out before starting the evaluation. They had the option of using a dumbbell of similar weight to be consistent in their evaluation and consequently not always over-power and win against the opposing ball. There was no restriction on the number of trials. Upon completion, the participants were asked to record their evaluation by classifying the opponent movement (pre-recorded data point) into *normal* or *impaired* classes. Following the trials, we interviewed the participants with a questionnaire consisting of questions from a system efficacy perspective on a 7-point Likert scale with a 1-7 range.

5.2.3 Results. Ease and Simplicity: The system fared favorably in terms of ease and simplicity theme as seen by the high mean for this part as shown in Table-3 and generally higher scores as seen in Figure-7. The questions pertained to, (E1) whether an effective evaluation was possible, (E2) ease of use, (E3) visual appeal, and (E4) ease in learning the system. The results for this section indicate that the system was appealing to SMEs in terms of learning its use and the visual presentation of the virtual environment and in-game interaction.

Quality of Experience for SMEs: The result for the Quality of Experience theme, although favorable, had a lower score than ease of use and shows some potential for further improvements. Some of the questions for which the system seemed favorable pertained to, (Q1) smooth operation and responsiveness, (Q2) experiencing no technical difficulties, and (Q5) potential to enhance current examination procedures. However, the participants down scored other questions such as (Q4) "*whether the system had all the necessary features to collect complete strength information*" and (Q3) "*how useful it was for an evaluation in isolation*". The scores seen in Table-3 and Figure-7 reflect this duality and show the scope for improvement. Such scores are expected since the system is not designed to outperform mechanisms to capture ground truth strength values but instead aims to provide approximate but robust and consistent estimates.

Comparison with In-Person and Tele-Health: Finally, the participants were asked to compare the system with both in-person and telehealth assessments based on an audio-video call. Here, P represents comparison with in-person procedures, and T represents comparison with telehealth. The questions were about comparing Virtepex in terms of (P1 / T1) being at least as effective as the standard, (P2 / T2) obtaining strength feedback, (P3 / T3) user engagement, (P4 / T4) being better than the standard, and (P5 / T5) the potential to replace the standardized assessment. Virtepex was preferred over a standard telehealth assessment (T) in all aspects, especially in obtaining data about the strength (mu=6). This indicates that even a coarse level of objective feedback from our system acts as a useful signal during the evaluation. As expected,

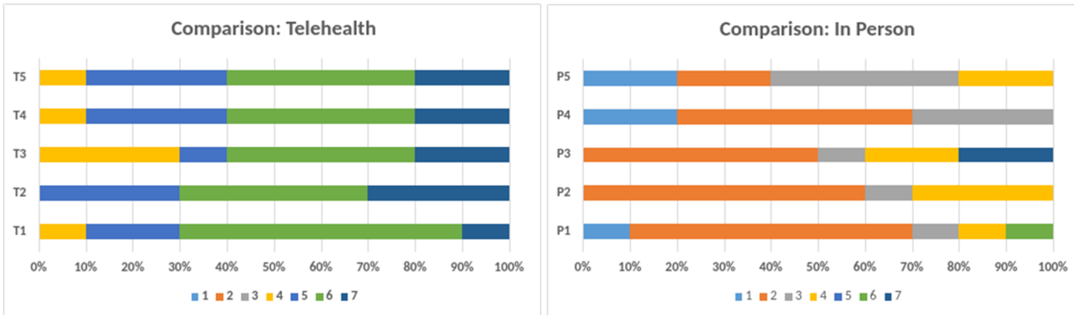


Figure 8: Stacked bar charts for comparison with In-Person and Telehealth evaluation for system efficacy study for SMEs (Section 5.2)

Table 3: Overall results from the system efficacy study for SMEs (Section 5.2)

Questionnaire Theme	Mean	Std. Dev
Ease and Simplicity	5.9	0.141
Quality of Experience	5.525	0.430
Comparison with In-Person assessment	2.7	0.505
Comparison with Tele-health assessment	5.72	0.179

the participants favored an in-person visit over Virtepex in terms of obtaining the strength feedback (mu=2.7). The overall score seen in Table-3 indicates the difficulty of replacing an in-person visit as the gold standard due to the benefits afforded by physical interaction.

5.2.4 Qualitative Results. We also collected qualitative feedback during the study, as a part of the questionnaires, and comments about specific topics at the end. We add a "P#" at the end of discussed qualitative results to highlight which participants shared similar responses. The overall judgment for the system seemed to be positive in terms of the potential to enhance current telehealth physical examination procedures and long-term remote physical evaluation of patients. The first subjective question was about comparison with telehealth exams with the question being: "What aspects of the physical exam were you able to effectively perform with this system which you were not previously able to do via standard telehealth (audio-video only) evaluation?" In this regard, participants seemed to favor having some level of information about the strength via the force estimates (P3, P4, P7, P8, P9) perhaps due to a "*better able to eval strength of patients and ROM*" (P3). Apart from the force estimates, they liked the "*virtual physical interaction with patients*" (P2) and "*isolated muscle evaluation*" (P1) aspects of Virtepex.

To solicit feedback about the limitations of the system, we posed the following question: "What are some examples of limitations that you faced when using this system?" The major pain point revolved around the potential problem of first time operating the system and quickly grasping its functionality (P1, P2, P6, P8). This is understandable as non-technical providers might take some time to get used to the gesture controls and interactive virtual environments. The sensitivity of gesture control was also a possible issue in future interactions as alluded to by P3: "*The system was very sensitive, so a small movement would start it before I was ready. I could also see how some patients could become confused until they practiced the motions such as our older populations.*" Another limitation brought out was the "*variation between patient strength and provider strength*" (P7) which is understandable as it is inherent to all forms of patient-provider interactions. Note that Virtepex could here contribute by using a standardized scale to compare force measurements.

The last question was about patients: "What kinds of patient populations could benefit the most from this system?" The responses overwhelmingly centered around groups with remote care needs such as "*Patients with mobility limitations and reduced access to healthcare facilities*" (P1), "*stroke patients*" (P7), and "*our patients that have difficulty coming to the facility for frequent visits*" (P3). Another interesting response was "*younger patients who have ease of using technology*" (P2) since that group has a lower barrier towards adopting VR through early exposure to such technology. To conclude, the responses indicate that the participants valued the force feedback and the ability of Virtepex to enable a better version of the remote physical assessment for homebound groups.

5.3 User Experience Evaluation

The user experience study helped to bring out an evaluation of the system in terms of overall experience while performing the joint movements and recording the motion data into the system. While the focus of the contributions is enabling SMEs to obtain better assessments for their patients, the user experience study helps to validate the interactive aspects and force estimation consistency.

5.3.1 Participants. We recruited eight healthy participants with no apparent discomfort in upper-body joints for this study. All of them were recruited from the parent institution of the first author with an age range of 22 to 30 (mean = 25.8, std-dev = 2.31) and a gender distribution of 4 males and 4 females. At the beginning of the study, participants were asked about familiarity with mixed reality applications and gesture-based controls. There were two groups, one with a high level of familiarity, and another with low familiarity with a mean score of 3.375 on a 7-point Likert scale (-3 to 3 range).

5.3.2 Study Procedure. At the beginning of the study, the researchers gave a quick demonstration of joint movements and hand gesture controls. At the start of a session, users were asked to take some

Table 4: Confidence intervals (p=0.05) per scale (N=8) from UEQ-S toolkit for the user experience study (Section 5.3)

Scale	Mean	Std Dev	Confidence Interval
Pragmatic	1.906	0.886	(1.292, 2.520)
Hedonic	1.875	0.732	(1.368, 2.382)
Overall	1.891	0.561	(1.502, 2.279)

time to familiarize themselves with the virtual environment. Depending on the joint movement selected, they were then asked to perform the specific movements as prescribed by the SME. Initially, the participants were asked to play the PinHit game to get used to the actions and game controls. They were then asked to play the Midline scene to record their forces for the different joint movements. In the end, they filled out a questionnaire detailing their experience with the system. We utilized a modified and condensed version of the User Experience Questionnaire (UEQ-S) [45] due to its simplicity. In addition, we also asked participants about (1) the consistency of the force estimates for the action performed and, (2) whether the interactive game-like setting felt better when compared to a video call.

5.3.3 Results. Table-4 shows the average scores for the scales of the questionnaire with their confidence intervals of p=0.005. The results were obtained from the UEQ-S data analysis toolkit. The range differs from the earlier results due to the toolkit automatically adjusting the 1-7 Likert score ranges to -3 to 3. The overall score was higher than 0.8 with the individual scale mean close to 2. According to [45], this means that the system gave an overall positive user experience. The results for the additional questions were also positive in general (Q1: mean=2.1, std=0.8; Q2: mean=1.6, std=0.9) and indicate that majority of the users attribute a prominent level of agreement with the effectiveness and consistency of force estimation observed during the game.

5.4 Summary

The primary goal of the system evaluation studies was to validate Virtepex from a physician's perspective as the primary contribution lies toward adding value for physicians. We reflect on the key findings from the results across the two sets of evaluation experiments below:

- Virtepex fared quite well in terms of its ease of use, virtual environment, and in-game interaction from an SME perspective. Such aspects are crucial to enable wider adoption of the system amongst physicians unfamiliar with VR and to ensure that the assessments are not a chore for end-users.
- Our system was favored by SMEs over a standard telehealth assessment as they preferred the signal from the high-level but objective feedback. Virtepex did not compare as favorably against an in-person assessment which was expected since explicitly replacing or modeling in-person visits was not the design goal.
- Some of the results from the Quality of Experience for SMEs show the scope for future improvement of Virtepex. Although there were no technical inconsistencies in its operation, few of the experts felt that more information could be collected to support enhanced feedback.
- The user experience evaluation study also supports the takeaway from the first point, albeit from a patient's perspective. The participants were satisfied with the consistency of force estimates and how effectively the force values were transferred to the game environment.

6 DISCUSSION

The needs assessment survey brought out the issue of current remote strength evaluation methods lacking objective metrics. Additionally, it showed that the physicians were not inclined to adopt complex rehabilitation systems and stressed the system setup ease for enabling real-world adoption. To the best of our knowledge, Virtepex is a novel system to tackle such challenges involved in strength rehabilitation. Our experiments hint toward the utility of including a marker-less force computation for approximate, but principled feedback. The marker-less force estimation is novel in the context of rehabilitation exergames, and hence our paper could contribute to motivating future designs of similar systems. Virtepex does not have any complicated procedure for the camera setup, nor does it impose any discomfort on the users during their movement as their actions are only constrained by the physician's instruction. The system evaluation results point towards the benefit of hand gestures and a mixed-reality environment for easy-to-use and interactive assessment sessions.

6.1 Limitations

Several challenges and limitations were observed during the iterative design process. A key limitation of Virtepex is the granularity of force estimation. The force estimation module cannot compute high precision force values due to the marker-less approach. In practice, this limitation is sometimes compounded with hard to detect joints such as the wrist or ankles. The Kinect v2 camera captures depth at a low resolution which can affect the accuracy of hand gesture recognition. Users with no prior experience with gesture-based control may take additional time to learn its use. Virtepex also requires that the specified joint should be visible to the camera for accurate 3D inference which can lead to erroneous and noisy estimates for an occluded joint. We would like to note that the system is not designed to replace an in-person evaluation but rather, to provide objective feedback for remote assessment. The force estimation method is not targeted for high precision, instead, it is designed to maintain relative consistency across different strength levels. The participants in our user study were from the young adult age group. Therefore, a distribution shift is expected when the system is deployed to a hospital where most of the patients skew towards an older age group. However, the SMEs pointed out that the expected movements from such patients should not differ significantly as the patients follow the prescribed movement within their comfort level.

6.2 Future Work

A potential line of future work involves incorporating a monocular RGB camera [34, 46] or newer depth cameras like the Intel RealSense or Microsoft Kinect Azure to track and provide the skeleton information. These could bring potential improvements in comparison to the Kinect v2 which is not actively supported by Microsoft. Similarly, using an RGB-only camera will probably improve the usability and convenience for patients. Here Virtepex can leverage laptop cameras with state-of-the-art deep learning models for monocular human pose estimation. A simultaneous direction would be to develop real-time and lightweight skeleton inference systems (e.g., BlazePose [3]) from the deep learning models and integrate them with the overall force estimation pipeline. It should be noted that although current deep learning models show promising results, most lack uncertainty information about their predictions. However, knowledge of such uncertainty in model predictions is vital in the healthcare domain, and hence, this could be a possible direction for future work. We also plan to carry out extensive patient trials at a local Veterans Affairs hospital with the visiting patients in PM&R (Physical Medicine and Rehabilitation).

7 CONCLUSION

Virtepex is a proof-of-concept system that proposes force estimation based on marker-less motion-capture for facilitating physicians in the remote assessment of body joints. The non-invasive tracking and force estimation module enables Virtepex to overcome the challenges with standard tele-rehab procedures. We designed Virtepex to lie between the two extremes of video-chat assessments (simple but no objective feedback) and on-body, sensor-based systems (precise values but complex setup). In this paper, we present the iterative design process and the guidelines set by SMEs. Further, we contribute with user studies with a primary focus on usability and effectiveness of the system from a physician's perspective. The results from the user studies show the potential of Virtepex and related force estimation methods in becoming a core component of remote, in-home rehabilitation and physical examinations.

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A FORCE ESTIMATION DETAILS

A.1 Joint Modeling

The joint motion is constrained to one degree of freedom namely rotation around a fixed axis. Hence a revolute joint shown in Figure-9 is an appropriate model. The inverse dynamics solver is implemented in Unity C# for lower computation overhead and instant force feedback inside the gamified virtual environment. Inside the environment, Unity's physics engine handled the simulation of the resulting motion and interaction of virtual objects in a physically plausible manner.

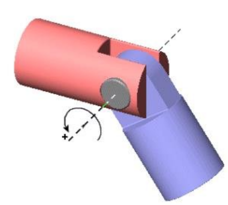

Figure 9: Illustration of a revolute joint with the rotation axis

A.2 Joint Angle Computation

As discussed previously, we consider the three upper body joints of the elbow, shoulder, and wrist with flexion/extension movement for all of them and the abduction movement for the shoulder joint. From the 3D position data provided by Kinect for the tracked body joints, we compute the joint angles using dot product between the 3D position vectors as follows. Note that the methods listed below are for the right-side joints of the skeleton diagram (see Figure-10 for the Kinect skeleton's joint numbering information). In terms of notation, the vector between two joints (i, j) is simply given by the difference of their respective 3D vector coordinates: pos(i) – pos(j). The angle between two vectors is then found using the dot product.

- Elbow: The angle between the vectors formed by location of joints (5,7) and (7,9).
- Wrist: The angle between the vectors formed by location of joints (7,9) and (9,13).
- Shoulder: The angle between the plane (torso) formed by joints (4,5,16) and the vector between joints (5,7).
- Shoulder Abduction: The angle between the vectors formed by location of joints (3,16) and (5,7).

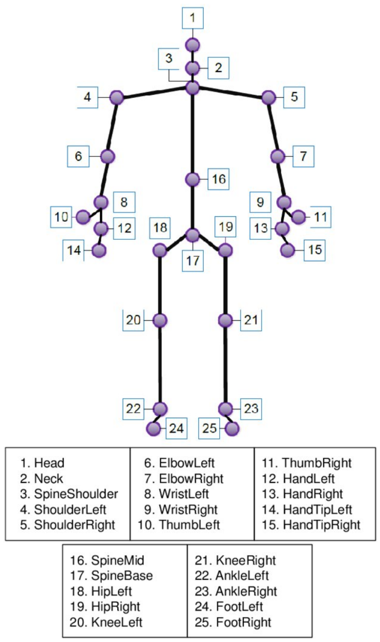

Figure 10: Kinect Skeleton

A.3 Force Estimation: Inverse Dynamics Algorithm

Based on the above modeling assumptions, we estimate force/torques acting on the joint using an inverse dynamics algorithm. Note that this is different from kinematics which is concerned with the motion of a rigid body. With Virtepex, we want to focus on the forces that cause the observed motion. It is an inverse problem because we know the start and end positions for the joint (and time) and are trying to estimate the force or torque (for rotational motion) that would have caused such motion. For a revolute joint, the motion is rotational in nature. Inverse dynamics is commonly employed in robotics and biomechanical analysis and there exist several approaches for formulating the problem. One such approach is via the Lie group formulation [30] which is an elegant way of considering both rotation and translation in a combined manner. Our modeling assumption treats the joint as an open-chain robot with gravity acting on the end of the chain. The vectors described in the previous sub-section can then be thought of as the links with the single revolute joint connecting them. Hence, we can then pose the force estimation problem in the setting of open-chain dynamics. To solve for the force values, we used the Newton-Euler approach which builds upon the generalization of Newton's second law of motion [36], namely, force is equal to mass times acceleration. The Newton-Euler approach requires information about the joint variable (e.g., the angle of rotation for revolute joint) and their time derivatives namely, velocity and acceleration. It proceeds recursively from the inward (proximal) to the outward (distal) link in the chain. A complete formulation of the algorithm is beyond the scope. Interested readers are encouraged to read more about the algorithm in [36]. [30] is an excellent resource for understanding the Lie Group formulation.

B DATA LOGGING TOOLKIT

For testing across multiple users, the asynchronous setting necessitated a data recording and logging mechanism for a storing an user's in-game performance. We added the functionality to create user profiles and record all relevant data during the rehabilitation and evaluation session. For each user, we logged information such as user-identifier (numeric id), joint, right/left hand, range of motion, time, estimated force, pin weight, etc. in an SQLite database.

C USER STUDIES

C.1 System Efficacy and Evaluation by SMEs

As noted in section 5.2, we evaluated the system along the four themes and the questions for each theme are noted below.

- Ease and Simplicity

(1) I was able to efficiently complete my evaluation using this system
(2) The system was easy to use
(3) The system was nice to look at
(4) It was easy to learn to use the system

- Quality of Experience for SMEs

(1) Smooth and Responsive device.
(2) There were no technical difficulties or interruptions during the session
(3) I believe the virtual assessment using the system was helpful for my evaluation
(4) The system had all the necessary functions and capabilities I expected to be able to collect valuable strength data from the patient
(5) Overall, I believe this system has the potential to enhance current telehealth physical examination procedures

- Comparison of Virtepex with in-person

(1) The system allowed me to physically evaluate the patient at least as effectively as I would in a standard in-person evaluation
(2) In comparison to a standard in-person evaluation, it was as easy or easier to get strength data from the patient using this system
(3) In comparison to a standard in-person evaluation, this system allowed for more patient engagement.

(4) Overall, I believe this system is better than a standard in-person evaluation.
(5) Overall, I believe this system has potential to replace standard in-person clinical evaluation

- Comparison of Virtepex with tele-health

(1) The system allowed me to physically evaluate the patient at least as effectively as I would in a standard telehealth (audio-visual only) evaluation
(2) In comparison to a standard telehealth evaluation, it was as easy or easier to get strength data from the patient using this system
(3) In comparison to a standard telehealth evaluation, this system allowed for more patient engagement
(4) Overall, I believe this system is better than a standard telehealth evaluation
(5) Overall, I believe this system has potential to replace the current standard of telehealth technology

C.2 User Experience Evaluation

The UEQ-S questionnaire was used along with its data analysis toolkit [38] for this study. Although the questions are standardized, there was context added to the questions to help the participants in answering. We also added a question on experience with AR/VR devices at beginning of the survey. The following list is the set of questions used:

- High degree of experience in usage of AR/VR devices
- Supportive (In Setup of System)
- Easy (In Ease of Use)
- Efficient (In Force Estimation Consistency)
- Clear (In Instructions and how to use)
- Exciting (In Overall experience)
- Interesting (In Usage)
- Inventive (In Novelty)
- Leading Edge (In Technology)
- Responsiveness of system (Less delay in force estimation)
- High degree of Help (In aiding remote assessment)