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Comparison of in-person and synchronous remote musculoskeletal exam using augmented reality and haptics: A pilot study

Aleks Borresen MD[1] | **Keerthana Chakka BS**[2] | **Richard Wu BS**[2] | **Chung-Kuang Lin MD**[3] | **Cody Wolfe MD**[4] | **Balakrishnan Prabhakaran PhD**[5] | **Thiru M. Annaswamy MD, MA**[6]

[1]Department of Physical Medicine and Rehabilitation, University of Alabama at Birmingham, Birmingham, Alabama, USA

[2]UT Southwestern Medical School, Dallas, Texas, USA

[3]Riverside Community Hospital, Riverside, California, USA

[4]Department of Neurosurgery, UT Southwestern Medical Center, Dallas, Texas, USA

[5]Department of Computer Science, Erik Jonsson School of Engineering and Computer Science, The University of Texas at Dallas, Richardson, Texas, USA

[6]PM&R Service, VA North Texas Health Care System, Department of PM&R, UT Southwestern Medical Center, Dallas, Texas, USA

Correspondence

Thiru M. Annaswamy, MD, Department of Physical Medicine & Rehabilitation, Penn State Health Rehabilitation Hospital 1135 Old W. Chocolate Ave., Hummelstown, PA 17036.
Email: tannaswamy@pennstatehealth.psu.edu

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Abstract

Introduction: Utilization of telemedicine for health care delivery increased rapidly during the coronavirus disease 2019 (COVID-19) pandemic. However, physical examination during telehealth visits remains limited. A novel telerehabilitation system—The Augmented Reality-based Telerehabilitation System with Haptics (ARTESH)—shows promise for performing synchronous, remote musculoskeletal examination.

Objective: To assess the potential of ARTESH in remotely examining upper extremity passive range of motion (PROM) and maximum isometric strength (MIS).

Design: In this cross-sectional pilot study, we compared the in-person (reference standard) and remote evaluations (ARTESH) of participants' upper extremity PROM and MIS in 10 shoulder and arm movements. The evaluators were blinded to each other's results.

Setting: Participants underwent in-person evaluations at a Veterans Affairs hospital's outpatient Physical Medicine and Rehabilitation (PM&R) clinic, and underwent remote examination using ARTESH with the evaluator located at a research lab 30 miles away, connected via a high-speed network.

Patients: Fifteen participants with upper extremity pain and/or weakness.

Interventions: Not applicable.

Main Outcome Measures: Inter-rater agreement between in-person and remote evaluations on 10 PROM and MIS movements and presence/absence of pain with movement was calculated.

Results: The highest inter-rater agreements were noted in shoulder abduction and protraction PROM (kappa (κ) $=$ 0.44, confidence interval (CI): -0.1 to 1.0), and in elbow flexion, shoulder abduction, and shoulder protraction MIS ($\kappa = 0.63$, CI: 0 to 1.0).

Conclusions: This pilot study suggests that synchronous tele-physical examination using the ARTESH system with augmented reality and haptics has the potential to provide enhanced value to existing telemedicine platforms. With the additional technological and procedural improvements and with an adequately powered study, the accuracy of ARTESH-enabled remote tele-physical examinations can be better evaluated.

INTRODUCTION

The coronavirus disease 2019 (COVID-19) pandemic led to accelerated adoption of telemedicine services in a variety of health care fields,[1–3] including many physical medicine and rehabilitation (PM&R) practices.[4] This swift transition highlighted both the potential benefits and limitations of telemedicine.[5] Prior to the COVID-19 pandemic, telemedicine had been used widely in fields such as psychiatry, dermatology, and radiology, where exchange of only visual and auditory inputs was largely sufficient.[6] However, telehealth visits that required hands-on interactions, such as those requiring physical exams or procedures, were significantly limited. Addressing these limitations could improve the utility of telemedicine for clinical care that commonly occurs in PM&R practices, and potentially improve health care delivery in other areas that utilize telemedicine, such as wilderness medicine,[7] disaster medicine,[8,9] global health,[10,11] and space medicine.[12–14]

Current telehealth systems allow health care providers to remotely assess patients' range of motion (ROM) and concentric/eccentric strength by asking the patient to move an extremity or pick up an object of known weight, and so on.[15,16] However, such assessments are limited by the constraints imposed by the audio/video (A/V)–only medium of interaction. A/V-based remote assessments can be enhanced with the assistance of a second health care provider at the remote site who assists in instructing and performing the exam on the patient while the primary health care provider directs and documents this remote assessment. Technologies that enable remote assessments to be performed without the need for this second health care provider at the remote site can therefore be valuable.

Augmented reality (AR), a technology that overlays computer-generated graphics on top of the user's physical surroundings, and virtual reality (VR), in which users are immersed in a constructed environment, have been used in telerehabilitation to manage orthopedic[17–19] and neurologic impairments.[18,20–22] VR and AR are often combined with haptics—a technology that transmits tactile (cutaneous/touch) and force (kinesthetic) feedback information. A common example of "vibro-tactile" haptic feedback is the vibration felt while typing with the onscreen keyboard of a smartphone. Force feedback provided by haptics is utilized by robot-assisted surgery devices and has applications in training motor tasks.[23] The combination of VR, AR, and haptic technology has been successful in the rehabilitation of upper extremity impairment[24–26] and has shown promise for use as assessment tools.[27] Extended reality (XR), an extension of this approach that combines VR or AR with devices such as wearables, sensors, and robots, has been used in telerehabilitation and shows promise for more personalized medicine.[28–32]

Using the XR approach, we designed and developed an Augmented Reality-based Telerehabilitation System with Haptics (ARTESH) for synchronous remote examination of upper extremity strength and ROM, without the need of a second health care provider at the remote site. ARTESH was tested and reviewed by clinician users, the details about which have been previously published.[33] ARTESH utilizes haptic technology and depth-sensing cameras to transmit real-time force and movement data between a patient and provider during a telemedicine visit.

TABLE 1 Clinical diagnosis responsible for upper extremity impairment in study participants

Diagnosis	Number of participants
Degenerative joint disease (DJD)	4
History of stroke	2
Impingement syndrome	2
Rotator cuff tear	2
Cervical spinal stenosis	1
History of shoulder surgery	4

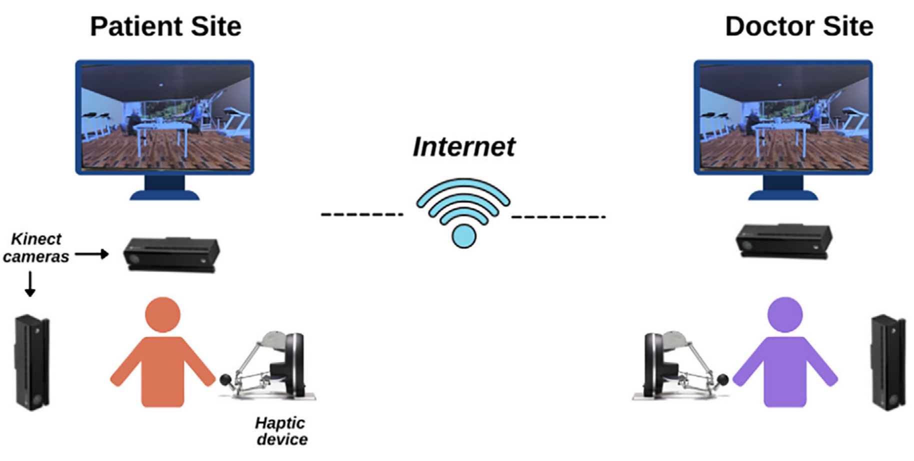

FIGURE 1 ARTESH Setup Schematic. Each site was equipped with two Xbox Kinect RGB-D cameras, one haptic controller, a 3D-capable TV, active 3D glasses, and a computer. A captured still image of the users' 3D environment is shown on the television screens. The computers were networked via the Internet, with audio, video, and force data transmitted in real-time between the two sites. (3D, 3-Dimension;TV, Television; RGB-D or red, green, blue plus depth)

Diagnosis made during an in-person visit has been found to have high agreement with remote diagnosis made via telehealth assessment.[34] However, to our knowledge, this is the first study of a synchronous, telephysical examination system to incorporate real-time exchange of force/strength information. In this pilot study, our objective was to evaluate the potential of using ARTESH to perform synchronous, remote physical examination in a pilot sample of patients with upper extremity impairment. Pilot inter-rater agreement data comparing remote exam findings to in-person exam findings obtained in this study will inform a future, adequately powered study to evaluate agreement with sufficient reliability. Another potential future study would be to evaluate clinical implementation of ARTESH in telemedicine clinics.

METHODS

ARTESH is a synchronous telemedicine delivery system that utilizes force feedback and depth-sensing camera technology to remotely transmit A/V and haptic data between a telehealth provider and patient. The system is composed of commercially available hardware combined with proprietary software. The AR component of the system is achieved using two depth-sensing Kinect for Windows v2 cameras, which capture three-dimensional (3D) video of a user's body. This avatar is then placed in real time into a virtual 3D environment. The sense of touch is accomplished using a Force Dimension Omega.3 Haptic Controller, which transmits a user's force in real time between the patient and physician sites. The two sites are connected through the Internet, and both users can interact remotely via touch and immersive video (Figure 1). The 3D environment surrounding the users, which was rendered using the Unity game engine, allows for a variety of different environments, as well as different camera angles. The maximal rendering force of the Omega.3 Haptic Controller device is 12 Newtons with an operating volume of 270 mm × 300 mm × 350 mm. Technical details of the ARTESH system have been published previously.[33,35,36]

In this pilot study, the ARTESH system was used to remotely examine the upper extremities of 15 research participants. The sample size of this pilot study was based on similar clinical studies of telerehabilitation technology reported previously in the literature.[37] Study participants were recruited from patients referred to a hospital-based PM&R, Physical Therapy, or Occupational Therapy clinic with a chief concern of arm or shoulder pain or weakness. Participants with a variety of diagnoses including adhesive capsulitis, glenohumeral arthritis, labral/rotator cuff pathology, and weakness/spasticity secondary to stroke were included in the study (Table 1).

Once a focused history was obtained, a physical examination of the arm and shoulder was undertaken by two separate clinicians within an hour of each other: one clinician performed an "in-person" evaluation while the other was trained in the use of the ARTESH system and performed a "remote" evaluation; the two clinicians were blinded to each other's evaluations. During the remote physical examination (Figure 2), passive ROM (PROM) and maximum isometric strength (MIS) were evaluated for 10 movements—elbow flexion and extension, shoulder elevation (or flexion), depression (or extension), internal rotation, external rotation, abduction, adduction, protraction, and retraction. PROM was assessed synchronously remotely by having the patient grip the haptic device with their hand while relaxing the arm and shoulder and having the evaluator move the patient's arm through the various 10 movements. MIS was assessed remotely by having the patient hold the haptic device stationary while the evaluator attempted to overcome the patient's strength with a force applied in the opposite direction. "In-person" PROM and MIS were evaluated in standard fashion. Physical examination results were rated on a binary scale as being either normal or impaired. The presence or absence of pain during PROM and MIS assessment was also noted.

Inter-rater agreement was calculated and reported for each joint movement and research subject. First, for preliminary qualitative analysis, the raw percent agreement between the two evaluators was calculated for each movement for PROM and MIS (i.e., number of participants for which elbow flexion strength examination agreed ÷ total number of participants) and for each research participant. Subsequently, the primary quantitative analysis was performed by calculating kappa statistics with 95% confidence intervals (CIs) to quantify the magnitude of agreement between remote and in-person examinations for each movement (calculated across all participants). The strength of agreement of ranges of Kappa statistics were reported as poor, slight, fair,

FIGURE 2 Snapshot of Virtual Remote Physical Assessment with ARTESH. This image is a representation of the users' 3D environment when using the ARTESH system

TABLE 2 Inter-rater agreement on passive range of motion (PROM) examinations between remote and in-person evaluations

Passive range of motion (PROM)		**Research Participant no.**															**Kappa statistic**	
Joint	**Movement**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Kappa	CI
Elbow	Flexion	A	A	A	A	P	A	D	A	A	A	A	A	A	A	D	−0.07	−0.2 to 0.0
	Extension	D	A	A	A	A	A	D	A	A	A	A	A	A	A	P	NA	
Shoulder	Elevation	D	D	D	D	D	D	A	D	A	D	D	A	D	P	D	−0.09	−0.4 to 0.2
	Depression	A	A	A	A	P	A	D	A	A	A	A	A	A	A	P	NA	
Shoulder	Internal rotation	A	A	P	A	D	A	A	A	A	A	A	A	P	A	P	NA	
	External rotation	D	A	A	A	D	P	A	D	A	P	A	A	A	P	D	0.25	−0.2 to 0.7
Shoulder	Adduction	A	A	P	A	A	P	D	D	A	A	A	P	D	A	D	−0.11	−0.3 to 0.0
	Abduction	A	A	P	P	D	A	A	A	P	A	A	A	A	A	D	0.44	−0.1 to 1.0
Shoulder	Protraction	A	D	A	P	P	A	A	A	P	A	A	A	A	A	D	0.44	−0.1 to 1.0
	Retraction	D	D	A	P	D	A	A	A	P	D	A	D	A	A	D	0.15	−0.1 to 0.4
Percent agreement by subject (%)		60	70	90	90	50	90	60	70	100	80	90	90	80	100	30		

Key

A	Remote and in-person exams agreed on normal PROM and pain
A	Remote and in-person exams agreed on impaired PROM and pain
D	Remote and in-person exams disagreed on PROM (agreed or disagreed on pain)
P	Remote and in-person exams disagreed on pain but agreed on PROM
NA	"Not Applicable" for computing statistics because one rater has less than two evaluation results

Abbreviation: CI, 95% confidence interval.

TABLE 3 Inter-rater agreement on maximum isometric strength (MIS) examination between remote and in-person evaluations

Maximum isometric strength (MIS)		**Research Participant no.**															**Kappa statistic**	
Joint	Movement	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Kappa	CI
Elbow	Flexion	A	A	A	A	D	A	A	A	A	A	A	A	P	A	A	0.63	−0.0 to 1.0
	Extension	A	A	A	A	A	A	D	A	P	A	A	A	A	A	P	NA	
Shoulder	Elevation	A	P	A	A	A	A	A	P	A	D	P	A	D	P	D	0.44	−0.1 to 1.0
	Depression	A	A	P	A	A	A	D	A	P	D	A	A	A	A	P	−0.07	−0.2 to 0.0
Shoulder	Internal rotation	D	P	P	A	D	A	D	A	A	D	A	A	P	A	A	−0.11	−0.3 to 0.1
	External rotation	D	A	P	D	D	P	A	A	D	D	P	A	P	P	D	−0.02	−0.5 to 0.5
Shoulder	Adduction	A	A	P	A	D	P	D	A	A	A	A	A	A	A	D	−0.1	−0.2 to 0.0
	Abduction	A	P	A	A	D	A	A	A	A	A	A	A	A	A	A	0.63	−0.0 to 1.0
Shoulder	Protraction	A	A	A	P	D	P	A	A	P	A	A	A	A	A	A	0.63	−0.0 to 1.0
	Retraction	D	A	A	A	D	A	D	A	P	A	A	A	A	P	A	NA	
Percent agreement by subject (%)		70	100	100	90	30	100	50	100	90	60	100	100	90	100	70		

Key

A	Remote and in-person exams agreed on normal MIS and pain
A	Remote and in-person exams agreed on impaired MIS and pain
D	Remote and in-person exams disagreed on MIS (agreed or disagreed on pain)
P	Remote and in-person exams disagreed on pain but agreed on MIS
NA	"Not Applicable" for computing statistics because one rater has less than two evaluation results

Abbreviation: CI, 95% confidence interval.

moderate, substantial, and almost perfect.[38] Statistical significance was calculated using a two-sided Z test to test the null hypothesis of Kappa = zero. Finally, the overall percent agreement was calculated for both MIS and PROM for each participant (i.e., percent agreement across all joint movements for each patient).

This study was approved by our institution's committee on research ethics (institutional review board), and written informed consent was obtained for all human participants involved in this research study.

RESULTS

Fifteen participants completed the study, all were male (not unusual for the Veterans Affairs [VA] population), and the average age was 63 years. Table 1 lists their primary clinical diagnosis responsible for their upper extremity impairment.

ROM Assessment: Preliminary analysis revealed that the raw percent agreement between remote and in-person ROM exam ranged from 27% to 93%, with the highest agreements in shoulder protraction, shoulder abduction, elbow flexion, elbow extension, shoulder depression, and shoulder internal rotation, and the lowest agreement in shoulder elevation.

The kappa statistic of shoulder abduction and protraction PROM was 0.44; CI: −0.1 to 1.0.

Strength Assessment: Preliminary analysis revealed that the raw percent agreement between remote and in-person MIS exam ranged from 60% to 93%, with the highest agreements in elbow flexion, elbow extension, shoulder depression, shoulder abduction, and shoulder protraction, and the lowest agreement in shoulder external rotation.

The kappa statistic of elbow flexion, shoulder abduction, and shoulder protraction MIS was 0.63; CI: 0 to 1.0.

Percent agreement between evaluators by participant ranged from 30% to 100% for both PROM and MIS (Tables 2 and 3). Some outliers included Participants 15 and 5, who had the lowest level of agreement at 30% for PROM and MIS, respectively; excluding these outliers, percent agreement between evaluators by participant ranged between 50% and 100%.

DISCUSSION

The results of this pilot study suggested that remote physical examination of upper extremity ROM and strength performed with ARTESH matched up well with in-person assessments. Inter-rater agreements (kappa values) on MIS and PROM assessments of multiple movements were promising, albeit with wide CIs due to the small sample size of this pilot study. Prior works evaluating the reliability of standard musculoskeletal physical assessment show a comparable range of values.[39–43] For example, a study analyzing physical exam tests for upper extremity function showed inter-rater agreements of 52% to 88% for shoulder tests and 27% to 57% for elbow/wrist tests.[43] Therefore, the results from ARTESH are promising for future applications in telerehabilitation clinics; however, as a pilot study, there are limitations that will need to be addressed in future research if ARTESH is to be implemented successfully into clinical practice.

The evaluation of the physical examinations was performed on a binary scale (normal/impaired) instead of through a 5-point or 10-point ordinal scale that is used for manual muscle testing (MMT). We were interested primarily in high-level comparisons between the two systems of assessment before doing a comparison at a more granular level. In addition, this is a clinical validation study of new technology; as such, a fully powered, quantitative comparative study between the two systems was beyond the scope of this work.

One significant outlier that limited the ROM agreement measure was Patient 15, who scored 7 of 10 in PROM impairment during in-person evaluation, but scored 10 of 10, or normal, in PROM during remote exam (Table 2). His in-person exam was limited by pain, which resulted in restriction of PROM. However, during remote examination, his PROM was evaluated with an underhand grip and not the standard lateral grip because of pain. As a result, his PROM was assessed remotely as "normal". Thus pain perception explained the discrepancy between the assessments for this patient.

Another ROM outlier was shoulder elevation, which demonstrated significant disagreement between in-person and remote exams (Table 2). The issue likely arose from ARTESH's limitation of movement in the plane of motion for shoulder elevation when the shoulder was flexed forward. This forward shoulder flexion position utilized most of the distance that the haptic controller could travel away from its origin (0, 0, 0). Therefore, when vertical shoulder elevation was attempted, the haptic device's movement range was limited and thus afforded little opportunity for force ($f = ma$; where $a = \Delta v/\Delta t$ and $\Delta v = \Delta x/\Delta t$) information to be transmitted. In other words, very little information was transmitted when the patient vertically elevated their shoulder because the haptic device was already moved close to its maximum range in this plane of motion. Thus the remote exam for shoulder elevation PROM yielded results that were not accurate and did not match up with those of the in-person exam.

In addition, remote ROM exams were limited by the haptic device's functional volume (270 × 300 × 350 mm). When comparing video ROM assessments to haptic PROM assessments, it was apparent that some ROM deficits evident on video were not picked up by the haptic device. This was due to the relatively small functional volume of the haptic device and led to some discrepancies between in-person and remote exams. For future study, it will likely be necessary to use haptic devices that have a greater volume of motion to ensure that all clinically significant deficits can be discerned.

One other set of outliers could be seen in patients with certain musculoskeletal deficits or weaknesses. In particular, the MIS assessments of Patients 5 and 7 presented with 70% and 50% disagreement, respectively (Table 3). These patients had hand grip weakness secondary to stroke. And, therefore, they had difficulty grasping and interacting through the haptic device (Figure 2). This caused difficulty in remotely assessing MIS for their shoulder and elbow movements. During the in-person evaluation, the patient's grip was not a limitation to assessing their shoulder and elbow movements. This explains the discrepancies in in-person and remote evaluations for Patients 5 and 7. Adapting the haptic device to accommodate for grip impairment using a glove or wrist harness may be necessary in future studies. Such adaptations would also allow this technology to be usable by patients with other impairments.

One additional change that could improve the system's versatility would be a haptic device with higher force feedback capacity. This would allow a wider range of force input and detection. The maximum force delivered via ARTESH's haptic controller was capped below 12 Newtons due to concerns about network delays causing positive force feedback loops and potentially injuring users. One solution would be to improve the algorithms that mediate the interaction between users to eliminate the possibility of force feedback loops. In the current system, this may prove difficult due to the need for each machine to be able to provide equal, real-time influence over the other, which enables a high-fidelity interaction with measures of strength; that is, neither machine can be considered as "primary" during clinical evaluation. On the other hand, the subtlety of forces transmitted by the system could be improved using a haptic device with a larger force feedback and operating volume, as testing strength or tone over the full ROM could improve assessment accuracy.

Another potential avenue of research would be to combine this technology with wearable sensors that address some of the underlying limitations discovered during the initial testing of the ARTESH system. A wide range of wearable technology and sensors have emerged in recent years, enabling the real-time detection of biometric data such as force, speed, and spatiotemporal positioning; other telerehabilitation systems have integrated Kinect sensors to analyze joint position and evaluate movement, ROM, and other gait parameters.[44] Combining new ideas and emerging technologies can produce the innovation that cultivates progress in health care. In this respect, further research and exploration of the solution space for telemedicine and health care delivery is needed to advance global health and the field of medicine.

Finally, clinical applicability of ARTESH needs to be considered for future real-world implementation of the system. This pilot study focused specifically on two aspects of remote physical assessment: PROM and MIS. However, the ARTESH system needs further development so that it can be more useful for comprehensive remote physical assessment including ability to (1) evaluate muscles with less than anti-gravity strength (testing gravity eliminated joint movement), (2) evaluate spasticity/tone/cog-wheeling or rigidity, (c) compare pain levels during PROM (via haptics) with active ROM (via video), and (d) perform special testing (e.g., Neer's, Hawkins', Speed's, and O′Brien's test). This type of system has potential not only for remote assessment but also to facilitate remote therapies (e.g., remote delivery of occupational therapy). Other clinical implementation concerns that need further study include ease and efficiency of setup for both health care providers and patients, and cost-effectiveness of the ARTESH system when compared to standard asynchronous or synchronous video assessment. Ease of use of this system has been studied previously,[33] but more investigations into the practicality of utilizing such a system in a real-world (nonresearch) setting are needed.

LIMITATIONS

This pilot study of clinical validation of new technology had some limitations. First, the sample size was small ($n = 15$) and participants were primarily older, White, male veterans, thereby limiting this study's generalizability. Second, this pilot study had <80% power to detect the highest kappa statistic obtained in our study. It is estimated that 22 to 30 participants are needed to have 80% power to detect moderate agreement ($k = 0.6$) in a two-sided test[45] to compare ARTESH and standard of care. A larger, more adequately powered study designed to further quantify the magnitude of agreement/disagreement between the ARTESH system and in-person physical examinations is needed. Third, the ARTESH system is still under development and is currently not clinically available. Factors that may inform the adoption and clinical utility of such a system including ease and efficiency of setup, cost-effectiveness compared to current telehealth systems, patient-reported outcomes, user adoption and retention rate, and provider/patient satisfaction need further study. Fourth, the binary grading of PROM and MIS used in this study is not a clinically accepted standard. Finally, the study required ultra-high-speed Internet with high bandwidth and speed specifications, which means that the generalizability of this study is limited.[33]

The last limitation mentioned above is especially significant for clinical practice; in 2019, over 14 million Americans (including about 11 million in rural areas) lacked broadband connections that met the Federal Communications Commission's criteria for fixed advanced telecommunications capability.[46] Given that telehealth access is not free from health care inequities,[47,48] we recognize the importance of addressing such inequities to ensure that technologies such as ARTESH can benefit all patients, as opposed to just part of the population.

CONCLUSION

This pilot study suggests that synchronous tele-physical examination using the ARTESH system with augmented reality and haptics has the potential to provide enhanced value to existing telemedicine platforms. With additional technological and procedural improvements and with an adequately powered study, the accuracy of ARTESH-enabled remote tele-physical examinations can be better evaluated.

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DISCLOSURES

The authors declare that there are no conflicts of interest.

ORCID

Richard Wu https://orcid.org/0000-0002-1904-1203
Chung-Kuang Lin https://orcid.org/0000-0002-4811-7473
Thiru M. Annaswamy https://orcid.org/0000-0002-3969-9221

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