Development of a Telemedicine Neurological Examination for Spine Surgery

A Pilot Trial

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Study Design: This was a prospective cohort study.

Objective: The objective of this study was to design and test a novel spine neurological examination adapted for telemedicine.

Summary of Background Data: Telemedicine is a rapidly evolving technology associated with numerous potential benefits for health care, especially in the modern era of value-based care. To date, no studies have assessed whether.

Methods: Twenty-one healthy controls and 20 patients with cervical or lumbar spinal disease (D) were prospectively enrolled. Each patient underwent a telemedicine neurological examination as well as a traditional in-person neurological examination administered by a fellowship trained spine surgeon and a physiatrist. Both the telemedicine and in-person tests consisted of motor, sensory, and special test components. Scores were compared via univariate analysis and secondary qualitative outcomes, including responses from a satisfaction survey, were obtained upon completion of the trial.

Results: Of the 20 patients in the D group, 9 patients had cervical disease and 11 patients had lumbar disease. Comparing healthy control with the D group, there were no significant differences with respect to all motor scores, most sensory scores, and all special tests. There was a high rate of satisfaction among the cohort with 92.7% of participants feeling "very satisfied" with the overall experience.

Conclusions: This study presents the development of a viable neurological spine examination adapted for telemedicine. The findings in this study suggest that patients have comparable motor, sensory, and special test scores with telemedicine as with a traditional in-person examination administered by an experienced clinician, as well as reporting a high rate of satisfaction among participants. To our knowledge, this is the first telemedicine neurological examination for spine surgery. Further studies are warranted to validate these findings.

Key Words: telemedicine, telehealth, remote medicine, neurological examination, spine surgery, orthopedic surgery, spine surgery, neurosurgery, value-based care

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Telemedicine is a rapidly evolving virtual technology that facilitates clinician and patient interaction via remote telecommunications services. Currently, the novel coronavirus 2019 (COVID-19) pandemic has created a greater urgency in

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This study was approved by the Institutional Review Board at the Thomas Jefferson University Hospital. Each author certifies that his or her institution approved the human protocol for this investigation and that all investigations were conducted in conformity with ethical principles of research.

Dr Schroeder has received funds to travel from AO Spine and Medtronic. Dr Vaccaro has consulted or has done independent contracting for DePuy, Medtronic, Stryker Spine, Globus, Stout Medical, Gerson Lehrman Group, Guidepoint Global, Medacorp, Innovative Surgical Design, Orthobullets, Ellipse, and Vertex. He has also served on the scientific advisory board/board of directors/committees for Flagship Surgical, AO Spine, Innovative Surgical Design, and Association of Collaborative Spine Research. Dr Vaccaro has received royalty payments from Medtronic, Stryker Spine, Globus, Aesculap, Thieme, Jaypee, Elsevier, and Taylor Francis/Hodder and Stoughton. He has stock/stock option ownership interests in Replication Medica, Globus, Paradigm Spine, Stout Medical, Progressive Spinal Technologies, Advanced Spinal Intellectual Properties, Spine Medica, Computational Biodynamics, Spinology, In Vivo, Flagship Surgical, Cytonics, Bonovo Orthopaedics, Electrocore, Gamma Spine, Location Based Intelligence, FlowPharma, R.S.I., Rothman Institute and Related Properties, Innovative Surgical Design, and Avaz Surgical. In addition, Dr Vaccaro has also provided expert testimony. He has also served as deputy editor/editor of Clinical Spine Surgery. The remaining authors declare no conflict of interest.

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the need to accurately diagnose and treat patients remotely.[1] Strategies for implementing remote-access health care have been in existence since 1978, but the advent and widespread use of the internet and cellular technologies have helped telemedicine gain tremendous popularity over the past decade.[2] Patient consultations with 2-way videoconferencing, remote monitoring of vital signs, and transmission of images are just some examples of current-day telehealth applications.[3] Advocates argue that this technology is a viable and economical tool to improve health care access in remote geographic regions, provide greater in-home care, and reduce health care costs.[4–13]

Presently, telemedicine-based applications are employed in a variety of medical subspecialties, including ophthalmology, dermatology, orthopedic surgery, and neurology; and their deployment is expected to continue to grow annually.[14–18] Specifically within the fields of orthopedics and spine surgery, telemedicine advantages include the ability to diagnose simple clinical problems, as well as monitor patients after surgical procedures, or even track the progression of a chronic, neurodegenerative disease (ie, cervical myelopathy).[19–25] Telemedicine removes potential barriers to access, such as time, cost and distance of travel, while increasing access to care in underserved areas. In addition, it has been shown to be cost-effective for health care organizations by decreasing unnecessary emergency room visits, transfers, and readmissions.[26–29] In March 2020, as a result of the increasing need to evaluate patients remotely during the novel COVID-19 public health emergency, the Center for Medicare and Medicaid Services (CMS) has broadened regulations and payments for physicians using telehealth services.[30]

Although telemedicine has been widely implemented, there are evident shortcomings with its use when evaluating spine patients. Of particular concern is the difficulty encountered when assessing neurological function remotely through a 2-dimensional screen. Specifically, the inability to accurately assess a patient's motor strength, sensation, and neurological reflexes is problematic, especially when operative decisions based on these parameters are necessary. This project was designed to assess, with specific tools and guidance, whether a patient's neurological status could be assessed with certain reliability. Therefore, the aim of this study was to determine the feasibility and accuracy of a self-administered telemedicine neurological examination (TELE) for spine patients.

METHODS

Enrollment

After review and approval from the Institutional Review Board (IRB), a pilot trial was initiated at a single academic medical center. Patients presenting for a spinal clinic evaluation with complaints of cervical or lumbar disorders were enrolled in the disease (D) group. A second cohort of health care providers and clinical staff without spine disease, pain or neurological deficits were enrolled in the healthy control (H) group. Informed consent was obtained and instructions on how to complete each component of the trial were given to each patient (Appendix I, Supplemental Digital Content 1, http://links.lww.com/CLINSPINE/A154). A full set of inclusion and exclusion criteria for this trial are included in Table 1.

TABLE 1. Inclusion and Exclusion Criteria

Inclusion criteria
Between 18 and 69 y of age
Current or prior diagnosis of cervical or lumbar radiculopathy, or cervical myelopathy*
No previous spine surgery
Exclusion criteria
< 18 OR > 70 y of age
History of prior spine surgery
Existing neurological deficits other than primary, degenerative lumbar or cervical radiculopathy and/or myelopathy*
Participants unable to self-administer components of Telemedicine Neurological Examination

*Spinal disease participants.

Pilot Trial Design

Each participant underwent a detailed and comprehensive motor, sensory (light-touch), and special (proprioceptive, cerebellar, and myelopathy) neurological examination. This was completed twice, once by a fellowship-trained spine surgeon (SPIN), and once by a fellowship-trained physiatrist (PHYS). These clinicians graded upper extremity myotomes (deltoids, biceps, triceps, finger flexors, interossei) and lower extremity myotomes (iliopsoas, quadriceps, tibialis anterior, extensor hallucis longus, gastrocnemius-soleus complex) according to manual motor testing guidelines.[31] Upper and lower extremity dermatomes were tested in the appropriate topographic areas as noted in Table 2. Additional special neurological tests were included to evaluate gait, cerebellar functioning, proprioception, and myelopathy: (1) Rapid Alternating Movements; (2) Toe-Walking; (3) Heel-Walking; (4) Tandem Gait; and (5) Romberg Test. Finally, participants were given instructions on how to perform self-assessments for these motor, sensory, and special testing components via a

TABLE 2. Telemedicine Neurological Examination—Dermatomes Tested

Upper Limb (C5–T1)		Lower Limb (L2–S1)	
Dermatome	Topographic Area	Dermatome	Topographic Area
C5	Lateral side of shoulder	L2	Anterior thigh
C6	Dorsal surface of thumb	L3	Medial femoral condyle (proximal to knee)
C7	Dorsal surface of middle finger	L4	Medial malleolus
C8	Dorsal surface of little finger	L5	Dorsum of foot (second MTP joint)
T1	Medial antecubital fossa	S1	Lateral heel (calcaneus)

MTP indicates metatarsophalangeal.

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FIGURE 1. Examination room set-up. full color online

Telemedicine Examination. Each participant performed each function of the assessment in the same order while being recorded by a GoPro camera (GoPro Inc., San Mateo, CA) at a fixed distance (6 feet, 1.83 m) (Fig. 1). To reduce fatigue effects, individuals were given a defined rest period of 10 minutes between each set of neurological examinations. A flow-chart demonstrating each step of the protocol is illustrated in Figure 2. After completing the examination component of the pilot trial, each participant was asked to fill out a brief survey regarding the overall experience. Details regarding the pilot trial can be found in Appendix I (Supplemental Digital Content 1, http://links.lww.com/CLINSPINE/A154).

Traditional and TELE Components

Motor

The motor examination relied on counter forces defined by the examiner and graded by a fellowship-trained spine surgeon or physiatrist based on standards set forth by the International Standards for Neurological Classification

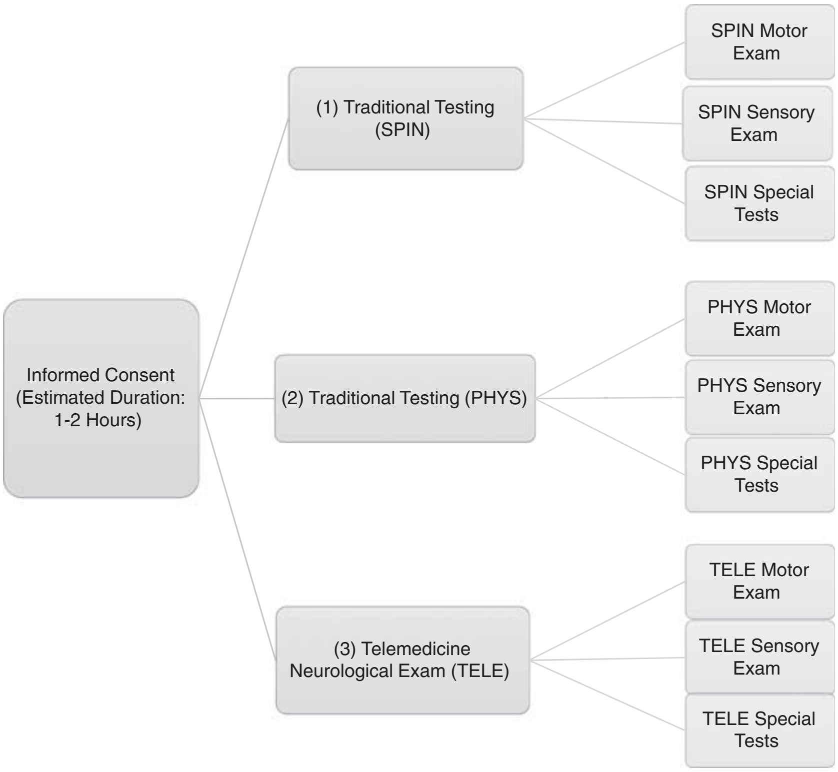

FIGURE 2. Pilot trial structure.

FIGURE 3. Telemedicine Neurological Examination Tools. Left, TheraBand resistance bands arranged in decreasing order of resistance (gold = most resistance; yellow = least resistance). Upper right, Semmes-Weinstein monofilaments arranged in ascending order of graded force (green = lowest force; red = highest force). Lower right, HerculesGrip ring and finger stretcher tools arranged in order of decreasing resistance from dark green to light green. full color online

of Spinal Cord Injury.[32] To have a consistent and objective motor component, the TELE employed 2 commercially available products: TheraBand resistance bands (Performance Health; United States) and the HerculesGrip grip ring and finger stretcher assessment tools (HerculesGrip; United States) (Fig. 3). Detailed motor function assessments are found in Table 3, and images correlating to these quantitative measurements are found in Figure 4. There was a self-assessed module to determine baseline muscle strength for each patient, after which participants determined the TheraBand or HerculesGrip resistance tool appropriate for their individual strength level self-examination. It should be noted that neither the TheraBand nor the HerculesGrip tools are approved by the Food and Drug Administration (FDA) for the intended use in this study.

Grading of the telemedicine motor component was based on performance in a full range-of-motion muscle motion incorporating tension bands as captured by the camera. This was quantified by the relation of predefined "peak-torque" angles (θ) as defined in the literature.[33–35] Individuals who stretched the band past a cutoff θ angle were considered to have full strength (5/5); whereas anyone able to perform an exercise against resistance (using any band) but not to θ was considered to have a motor deficit (4/5). These participants were further explored in terms of movement without resistance (only antigravity) (3/5). The ImageJ image processing software (National Institute of Mental Health, Bethesda, MD) was utilized to measure θ achieved for participants in each myotome.[36] Accounting for difficulty in accurately measuring θ for C8, T1, L2, and L5, these myotomes were graded based on whether participants were able to perform each movement against resistance or not (binary scale: 1 = able to perform movement against resistance tool; 0 = not able to perform movement against resistance). Details of the grading for the TELE and measurements of θ can be found in Table 4 and Figure 5, respectively.

TABLE 3. Telemedicine Neurological Examination—Myotomes Tested

Upper Limb (C5–T1)		Lower Limb (L2–S1)	
Myotome	**Action (Muscle)**	**Myotome**	**Action (Muscle)**
C5	Shoulder abduction (deltoids)	L2	Hip flexors (iliopsoas)
C6	Elbow flexion (biceps brachii)	L3	Knee extensors (quadriceps)
C7	Elbow extensors (triceps brachii)	L4	Ankle dorsiflexors (tibialis anterior)
C8	Finger flexors (FDS, FDP)	L5	Long toe extensor (extensor hallucis longus)
T1	Finger abductors (hand intrinsic muscles)	S1	Ankle plantar flexors (gastrocnemius, soleus)

FDP indicates flexor digitorum profundus; FDS, flexor digitorum superficialis.

Sensory

Traditional sensory testing relied on tactile fine-touch sensation and was graded by a fellowship-trained spine surgeon or physiatrist based on standards set forth by the International Standards for Neurological Classification of Spinal Cord Injury.[32] The sensory portion of the TELE employed Semmes-Weinstein monofilaments (SWM). Participants were asked to utilize SWMs in the self-assessment of C5–T1 and L2–S1 dermatomes (Table 2, Fig. 6). The sensory portion incorporated 2 SWMs, each tested 3 times. First, the baseline green monofilament (size 3.61) was used; if the monofilament triggered a sensation detected by the participant at least one of the 3 times, then sensation was considered to be

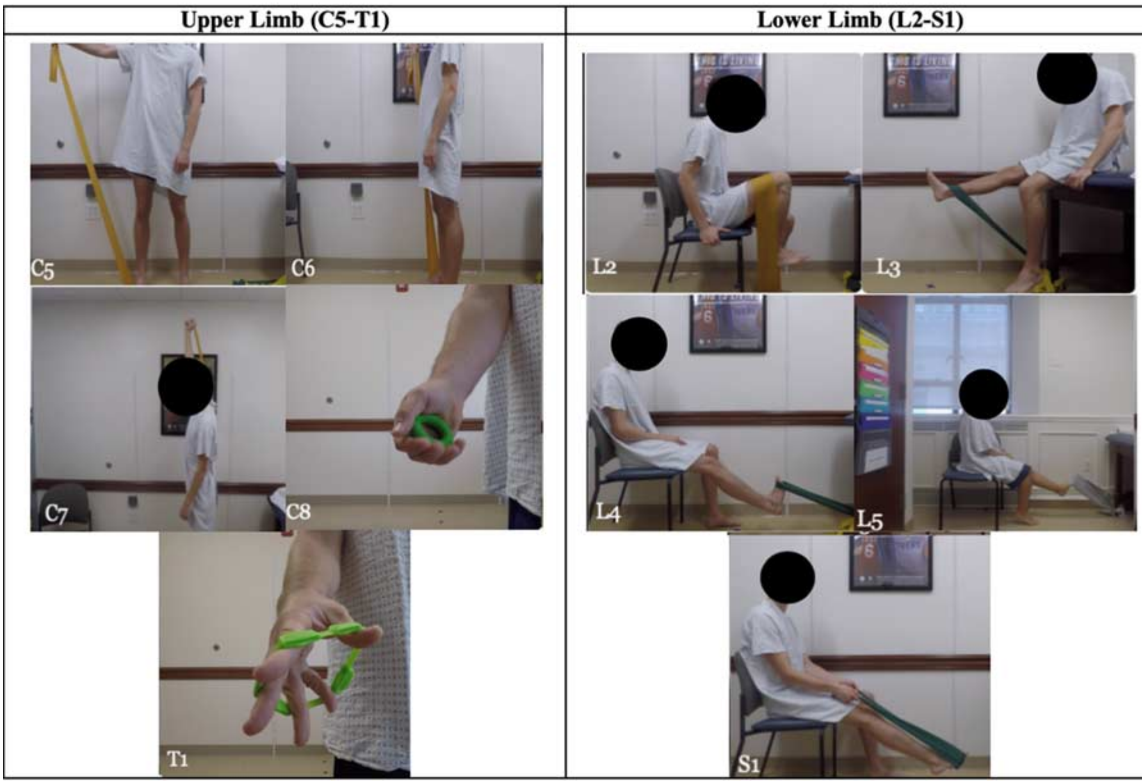

FIGURE 4. Telemedicine Neurological Examination—Motor Portion. full color online

intact in that particular nerve distribution and the patient received a score of 2/2 (normal) for light touch sensation. If the patient did not perceive light touch after 3 attempts with the green monofilament, then the red SWM (size 6.65) was used, repeating the 3 tests. If the patient perceived light touch at least 1 time, then a score of 1/2 (abnormal sensation) was recorded for that dermatome. The inability to perceive sensation in any of the 3 attempts with the red SWM was recorded as a 0/2 (absent sensation) in that specific nerve distribution.[37,38]

Special Tests

The special tests portion of the TELE included evaluating gross cerebellar functioning, proprioception, and myelopathy: (1) Rapid Alternating Movements; (2) Toe-Walking; (3) Heel-Walking; (4) Tandem Gait; and (5) Romberg Test. Special tests were graded based on a binary scale (1 = able to perform test; 0 = not able to perform test).

Details about the structure of the pilot trial and components utilized in the TELE arm can be found in Appendices I and II (Supplemental Digital Content 1, http://links.lww.com/CLINSPINE/A154).[39–45]

Data Collection/Statistical Analysis

Demographics and medical histories were collected and recorded for each participant via chart review. Motor, sensory, and special test grades by

TABLE 4. Telemedicine Neurological Examination—Motor Grading

Upper Limb (C5–T1)			Lower Limb (L2–S1)		
Myotome	**Peak-Torque (deg.) (θ) (95% CI)**	**Motor Score**	**Myotome**	**Peak-Torque (deg.) (θ) (95% CI)**	**Motor Score**
C5*†	33.5 (24.7–42.3)	5	L2‡	Any noticeable hip flexion against band	5
C6*†	60.0 (30.0–90.0)	5	L3*†	70.0 (50.0–90.0)	5
C7*†	70.0 (50.0–90.0)	5	L4*†	14.2 (1.3–27.1)	5
C8‡	Any observed deformation of HerculesGrip tools	5	L5‡	Any noticeable hallux extension against band	5
T1‡		5	S1*†	13.5 (3.4–23.6)	5

*When participant is unable to lift band up to low end of 95% confidence interval (CI), but demonstrable displacement against gravity: motor score = 4.
†When participant is unable to lift band against gravity, but able to demonstrate unresisted movement against gravity: motor score = 3.
‡Intactness of C8, T1, L2, and L5 motor function either intact (motor score = 5) or not (motor score = 3).

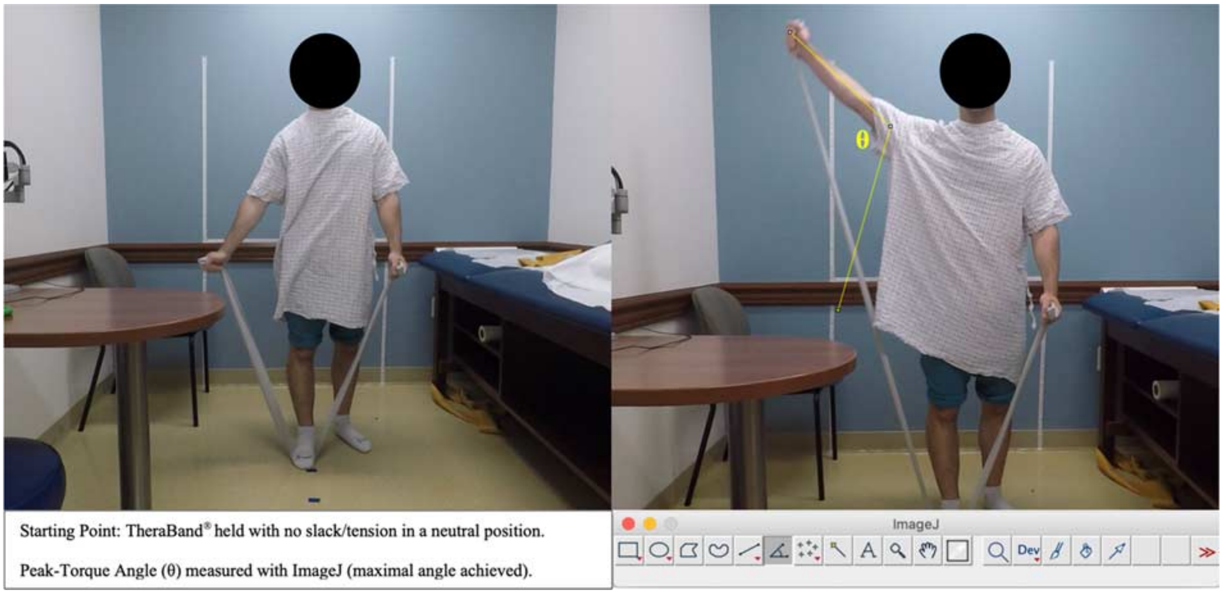

FIGURE 5. Peak-Torque Angle (θ). full color online

traditional means (SPIN and PHYS), and from the telemedicine TELE were compared via univariate analysis—Pearson χ^2 test. Overall satisfaction levels, pain/discomfort experienced during the examination, and additional free-form comments were queried and documented after participation in the trial.

RESULTS

Cohort

A total of 41 individuals were included in this pilot trial, with 21 (51.2%) healthy controls (H group) and 20 (48.8%) patients with known cervical or lumbar spine

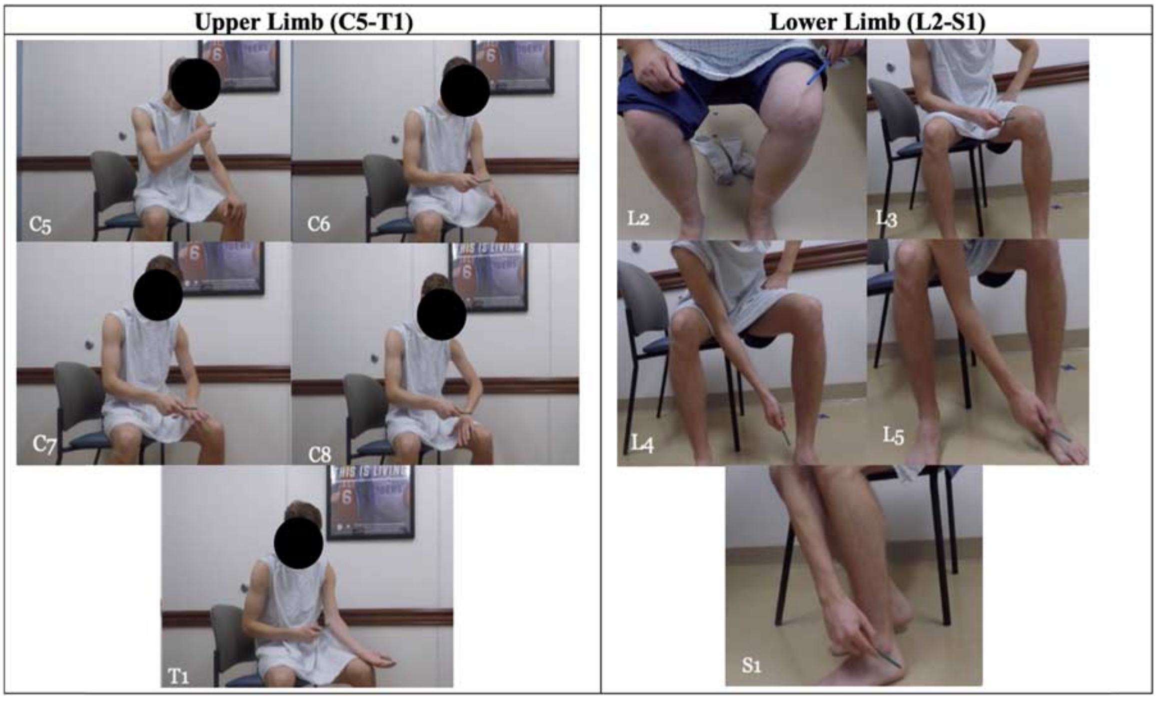

FIGURE 6. Telemedicine Neurological Examination—Sensory Portion. full color online

TABLE 5. Demographics and Medical History of Healthy (H) Participants

Participant	Age (y)	Sex	Height (Inch)	Weight (lbs)	Spine Disease	Neurological Issues	Medical History	Surgical History
1	27	Female	63	120			None	None
2	30	Male	70	230			None	Hernia repair
3	24	Male	69	180			None	None
4	55	Female	65	130			None	None
5	42	Female	62	134			ADHD, anxiety	Ectopic pregnancy
6	42	Male	72	165			Depression	Tonsillectomy; varicocelectomy
7	57	Female	63	215			Knee osteoarthritis	THA (bilateral)
8	32	Male	70	160	—	—	None	None
9	67	Male	67	190			Meniscus tear; perforated veins	Prostatectomy
10	40	Female	66	152			None	C/S×2; tubal ligation
11	32	Male	66	150			None	Tonsillectomy
12	28	Male	67	135			None	None
13	34	Female	65	160			None	None
14	68	Female	65	148			Rotator cuff tear; thyroid cancer (remote history)	Wrist fx s/p ORIF; clavicle fx s/p ORIF; thyroidectomy; cataract sx
15	63	Female	62	160			Knee osteoarthritis; MI (remote history—10 y ago)	None
16	42	Male	69	167			PUD	None
17	66	Female	70	200			RLS; HTN; HCL	Myomectomy; cataract sx
18	36	Male	69	225			HTN; hypothyroidism	None
19	66	Female	63	132			T2DM (controlled); gastroparesis; nephrolithiasis; Sjogren disease	Clavicle fx s/p ORIF×2; wrist fx s/p ORIF; C/S×3
20	58	Male	65	270			T2DM (controlled); HTN; pacemaker	Tibia fx s/p ORIF; pacemaker implantation
21	51	Male	67	200			Shoulder osteoarthritis	None

ADHD indicates attention deficit hyperactivity disorder; C/S, cesarean section; fx, fracture; HCL, hypercholesterolemia; HTN, hypertension; MI, myocardial infarction; ORIF, open reduction, internal fixation; PUD, peptic ulcer disease; RLS, restless leg syndrome; s/p, status post; sx, surgery; T2DM, type II diabetes mellitus; THA, total hip arthroplasty.

disease (D group). There were 20 (48.8%) males and 21 (51.2%) females, with 5 (12.2%) individuals between 18 and 29 years of age, 10 (24.4%) between 30-39 years of age, 7 (17.1%) between 40 and 49 years of age, 9 (21.9%) between 50 and 59 years of age, and the remaining 10 (24.4%) between 60 and 69 years of age. Detailed demographics, medical histories, and TELE motor/sensory tools utilized for each participant are summarized in Tables 5–7.

Traditional Versus TELE

There were no significant differences in motor scores observed via traditional neurological testing (SPIN and PHYS) and the TELE for any of the myotomes evaluated (C5–T1 and L2–S1) (Table 8). With regards to sensory testing, there was a significant difference in the right L4 dermatome, with TELE identifying more patients with diminished sensation (score 1/2, Tele = 4; SPIN = 0, PHYS = 0; $P = 0.02$). TELE, SPIN, and PHYS examinations were not found to significantly differ with respect to any of the other dermatomes included, or with respect to any of the special tests evaluated (Figs. 7–9). A majority of patients were "very satisfied" (92.7%) with their overall experience with the TELE compared with traditional testing, with 2 (4.9%) patients being "somewhat satisfied" and 1 (2.4%) being "neither satisfied nor dissatisfied" (Table 9).

DISCUSSION

Over the past decade, telemedicine has become an increasingly valuable clinical tool; something that became particularly evident during the COVID-19 pandemic.[1] Telemedicine has the potential to reduce health care costs, while simultaneously increasing access of specialized medical care to geographically restricted or underserved populations via virtual means. Decreasing costs without compromising quality may improve the ability to provide value-based care to patients. In spine surgery, this new virtual platform has the potential to change the way spinal disease, chronic neurodegenerative conditions, and postoperative care are managed. Nevertheless, a possible drawback of current telemedicine-based applications in spine surgery is the lack of a defined, quantitative and validated virtual clinical examination with motor, sensory and advanced components. The purpose of this study was to develop a novel neurological examination for use in remote telemedicine interventions and compare its

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TABLE 6. Demographics and Medical History of Spinal Disease (D) Participants

Participant	Age	Sex	Height (Inch)	Weight (lbs)	Spine Disease	Neurological Issues	Medical History	Surgical History
1	58	Male	66	190	Lumbar stenosis	Weakness (leg)	CAD, HTN	CABG
2	61	Male	63	194	Lumbar stenosis	Leg pain (radiating)	None	None
3	62	Male	72	188	Lumbar stenosis	Weakness (leg); numbness (toe); foot drop	None	None
4	67	Male	74	208	Lumbar stenosis	Numbness and tingling (foot, thigh, buttocks); balance/proprioceptive issues	BPH	TURP
5	54	Female	62	127	Lumbar radiculopathy	Leg pain (radiating)	HTN	Hysterectomy
6	36	Female	61	156	Cervical disk herniation	Arm pain (radiating); numbness (hand); occasional balance/proprioceptive issues (occasional)	HCL	C/S×3; rhinoplasty; abdominal hernia repair; breast reduction; trigger finger repair
7	69	Male	72	281	Lumbar stenosis	Bilateral leg pain (radiating)	AFib; trigger finger	TKA; rhinoplasty; cardiac ablation; trigger finger repair
8	55	Female	63	168	Cervical stenosis	Burning and tingling (arms and fingers); neck discomfort; headaches	GERD, trigger finger; endometriosis	Appendectomy; TFCC repair; labral repair (shoulder); laparoscopic exploration (endometriosis)
9	25	Female	66	150	Cervical disk herniation	Upper back/shoulder/arm pain (radiating); weakness (arm, hand); numbness (arm)	None	Breast adenoma removal
10	38	Female	63	122	Cervical stenosis; cervical disk herniation	Paresthesias (shoulder and arm); weakness (hand)	Anxiety	Wisdom teeth removal; breast augmentation
11	40	Female	69	166	Lumbar stenosis (foraminal)	Tingling (legs)	Migraine headaches	Bunionectomy; breast augmentation; appendectomy
12	67	Female	59	190	Lumbar spondylolisthesis	Leg pain (radiating); balance/ proprioception issues (occasional)	HTN	Mastectomy (bilateral); hysterectomy; appendectomy
13	58	Male	70	210	Cervical stenosis	Neck pain; shoulder pain (radiating)	GERD, RCC, GIST	RCC excision
14	36	Male	71	230	Lumbar disk herniation	Foot pain (radiating); numbness and tingling (leg)	None	ACL reconstruction (bilateral)
15	55	Female	62	185	Cervical disk herniation	Arm pain (radiating); coordination (finger); numbness and tingling (arm)	HTN, T2DM (controlled)	Liver transplant; THA
16	36	Male	69	200	Lumbar disk herniation	Leg pain (radiating); numbness and tingling (leg)	None	None
17	33	Female	64	185	Cervical disk herniation	Numbness and tingling (arm); weakness (arm, hand)	None	None
18	41	Female	69	240	Cervical radiculopathy	Arm pain (radiating); numbness (hand—median nerve)	None	None
19	47	Male	72	215	Cervical stenosis	Arm and hand pain (radiating)	HTN, HLD	Melanoma excision
20	28	Female	65	135	Lumbar radiculopathy	Leg pain (radiating); numbness and tingling (leg)	None	Wisdom teeth removal

ACL indicates anterior cruciate ligament; AFib, atrial fibrillation; BPH, benign prostatic hyperplasia; CABG, coronary artery bypass graft; CAD, coronary artery disease; C/S, cesarean section; GERD, gastroesophageal reflux disease; GIST, gastrointestinal stromal disease; HCL, hypercholesterolemia; HLD, hyperlipidemia; HTN, hypertension; RCC, renal cell carcinoma; s/p, status post; T2DM, type II diabetes mellitus; TFCC, triangular fibrocartilage complex; THA, total hip arthroplasty; TKA, total knee arthroplasty; TURP, transurethral resection of the prostate.

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TABLE 7. Telemedicine Neurological Examination Components

Group	Participant	Band Color	Grip Ring (C8) Size	Finger Stretcher (T1) Size	Semmes-Weinstein Monofilaments Size
Healthy (H)	1	3	1	3	1
	2	1	1	1	1
	3	1	1	1	1
	4	2	3	3	1
	5	5	2	3	1
	6	2	1	2	1
	7	5	1	1	2
	8	1	1	2	1
	9	2	1	2	1
	10	5	1	3	2
	11	2	1	1	1
	12	5	2	3	1
	13	2	1	3	2
	14	5	2	1	2
	15	3	1	3	2
	16	2	1	2	2
	17	5	1	3	1
	18	2	1	2	2
	19	7	1	1	2
	20	2	1	2	2
	21	4	1	2	2
Spinal disease (D)	1	1	1	1	1
	2	5	2	2	1
	3	2	1	2	2
	4	2	1	2	2
	5	2	2	1	2
	6	3	3	3	2
	7	5	1	2	2
	8	7	3	3	1
	9	3	2	3	1
	10	5	1	2	1
	11	2	1	1	2
	12	2	1	2	2
	13	3	1	2	1
	14	2	1	2	1
	15	7	1	1	1
	16	1	1	2	1
	17	3	2	2	1
	18	3	1	2	1
	19	3	1	2	1
	20	3	1	1	1

Band color sizing: 1 = gold; 2 = silver; 3 = black; 4 = blue; 5 = green; 6 = red; 7 = yellow.

Grip ring/finger stretcher sizing: 1 = darkest green; 2 = lighter green; 3 = lightest green.

Semmes-Weinstein monofilaments sizing: 1 = green (size 2.83); 2 = blue (size 3.61); 3 = red (size 6.65).

performance to traditional neurological examinations performed by experienced providers in the clinic.

Results from the present analysis demonstrate no significant differences in administered examinations with respect to motor scores obtained in all upper and lower limb myotomes tested (SPIN vs. PHYS vs. TELE; Fig. 7). This similarity in observations was maintained for all dermatomes tested in the sensory examination portion, with the exception of the right L4 dermatome, in which TELE detected diminished sensation (1/2) more frequently (Fig. 8; TELE = 9.6%; SPIN = 0.0%; PHYS = 0.0%; $P = 0.02$). The finding that a telehealth examination component is more sensitive in detecting patients with decreased light touch is likely due to the fact that SWM are more sensitive to deficits than traditional in-person examination maneuvers. Last, when considering special tests, there were no significant differences between groups (Fig. 9).

This pilot study suggests that spinal neurological examinations are possible via remote protocols administered with telemedicine applications. Several studies in the literature have also evaluated the impact and feasibility of telemedicine for postoperative management.[46–57] Sharareh and Schwarzkopf[53] evaluated the utility of telemedicine for patients after primary total hip arthroplasty or total knee arthroplasty. There were no significant differences between groups in terms of postoperative patient reported outcomes, American Society of Anesthesiology (ASA) classification, or activity scores.[53] Furthermore, Kane et al[55] evaluated telemedicine as a tool for managing rotator cuff repair rehabilitation in the postoperative setting, comparing pain scores, passive range of motion exercises, and qualitative outcomes among patients between remote and traditional outpatient office visits at various time points. The researchers found no significant differences between groups in the aforementioned outcomes at 2, 6, and 12 weeks postoperatively.[55]

One of the biggest advantages for incorporating telemedicine-based visits into more mainstream health care applications revolves around the noticeable patient satisfaction with this technology.[55,58–61] The aforementioned study by Kane et al[55] included an analysis of satisfaction, finding no significant differences between groups. The authors noted that patients who participated in the telemedicine arm reported a stronger preference for this form of postoperative monitoring than the non-telemedicine participants, implying that simple exposure to this technology increased the likelihood that patient's would opt to use this form of remote-based monitoring for their health care needs.[55] Buvik et al[58] noted similar trends in a separate randomized controlled trial comparing overall satisfaction scores between telemedicine-based videoconferencing and traditional in-person office visits for patients requiring orthopedic consultation. The authors noted high satisfaction rates for both groups (99.0% "satisfied" or "very satisfied"), and observed that patients in the telemedicine group would prefer to have this type of visit for the next consultation (86.0% vs. 63.0%) compared with the control group.[58] In each of these studies, while overall satisfaction scores were similar between telemedicine and in-office based groups, exposure to remote-based health care technologies significantly increased the preference for its use in future encounters. Although the present study did not directly evaluate preference for telemedicine in future visits, results suggest an overall high rate of satisfaction with the proposed TELE with 92.7% of participants feeling "very satisfied" with their overall experience. There were 2 participants who were "somewhat satisfied," both of which noted pain during portions of the upper extremity motor examination. One participant was "neither satisfied nor dissatisfied" and had commented that the "heel-toe" examination may be dangerous for

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TABLE 8. Telemedicine Neurological Examination Motor Examination—Observed Joint-Torque Angles

		Upper Limb Myotomes										Lower Limb Myotomes									
		C5		C6		C7		C8		T1		L2		L3		L4		L5		S1	
Group	Participant	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L
Healthy (H)	1	132.25	129.11	137.23	134.27	125.76	120.99	O	O	O	O	O	O	77.02	80.87	19.10	17.45	O	O	40.45	41.50
	2	130.27	124.38	141.61	132.42	126.87	135.89	O	O	O	O	O	O	85.08	82.03	17.89	18.34	O	O	46.48	44.94
	3	132.12	126.86	158.87	155.13	119.46	126.58	O	O	O	O	O	O	79.98	81.99	19.50	18.99	O	O	46.31	41.10
	4	155.43	155.53	142.82	149.04	127.80	131.18	O	O	O	O	O	O	75.26	77.17	17.83	17.66	O	O	43.97	42.74
	5	134.56	121.40	159.82	157.32	125.96	120.14	O	O	O	O	O	O	81.84	82.99	19.76	17.89	O	O	39.36	37.51
	6	152.50	151.91	137.25	141.35	133.35	138.16	O	O	O	O	O	O	99.70	94.59	16.16	17.06	O	O	43.39	42.01
	7	130.99	128.60	136.98	133.01	130.44	122.42	O	O	O	O	O	O	79.84	78.07	18.89	17.99	O	O	36.56	41.44
	8	126.56	117.61	129.54	133.51	122.88	111.13	O	O	O	O	O	O	98.95	88.07	17.67	18.17	O	O	37.95	38.15
	9	142.24	130.32	130.02	126.54	118.35	112.20	O	O	O	O	O	O	58.49	58.32	14.15	14.67	O	O	39.94	38.82
	10	139.79	126.33	141.44	144.47	132.04	125.33	O	O	O	O	O	O	70.84	73.24	17.54	17.33	O	O	47.26	45.42
	11	128.62	125.53	123.88	127.70	117.27	118.52	O	O	O	O	O	O	85.48	77.31	18.89	16.44	O	O	38.04	37.08
	12	117.28	119.63	135.64	131.67	120.96	109.79	O	O	O	O	O	O	83.85	72.81	19.56	19.05	O	O	38.83	39.72
	13	145.07	151.22	146.23	133.47	129.81	127.26	O	O	O	O	O	O	67.29	73.89	21.05	20.66	O	O	36.84	32.48
	14	156.47	147.52	137.76	130.44	150.92	147.13	O	O	O	O	O	O	76.37	71.70	16.78	17.58	O	O	45.91	44.42
	15	161.29	160.63	149.98	153.29	113.51	112.73	O	O	O	O	O	O	78.81	81.29	19.87	20.78	O	O	39.98	41.66
	16	119.07	122.88	136.12	125.82	119.07	115.02	O	O	O	O	O	O	73.89	70.59	15.67	15.99	O	O	41.57	37.39
	17	107.70	110.96	150.53	137.68	117.70	109.64	O	O	O	O	O	O	65.70	72.62	18.70	19.32	O	O	39.58	37.98
	18	128.97	129.50	143.97	134.28	125.31	123.65	O	O	O	O	O	O	67.33	66.07	18.88	19.54	O	O	39.36	38.03
	19	140.00	129.43	144.26	140.31	118.61	111.34	O	O	O	O	O	O	75.05	82.20	21.11	20.57	O	O	36.67	42.47
	20	152.68	138.33	128.09	126.19	136.80	126.35	O	O	O	O	O	O	78.01	68.64	17.54	18.33	O	O	43.36	40.43
	21	146.52	141.96	152.67	148.18	127.55	122.10	O	O	O	O	O	O	93.40	95.41	15.39	14.89	O	O	43.40	38.51
Spinal disease (D)	1	108.61	102.82	108.96	114.56	125.40	121.63	O	O	O	O	O	O	82.65	78.92	16.77	16.32	O	O	39.59	38.67
	2	122.10	114.28	134.09	116.72	127.14	116.76	O	O	O	O	O	O	79.75	81.23	18.95	19.99	O	O	38.36	40.90
	3	153.99	156.70	144.85	133.80	126.80	132.04	O	O	O	O	O	O	75.39	70.08	16.54	14.90	O	O	43.44	42.27
	4	135.60	144.77	146.95	147.06	116.15	123.13	O	O	O	O	O	O	78.24	77.60	16.70	15.43	O	O	43.65	40.98
	5	112.84	125.98	132.66	140.84	110.86	118.67	O	O	O	O	O	O	94.88	91.46	18.95	19.67	O	O	32.65	32.18
	6	128.72	125.68	119.53	125.26	117.25	112.22	O	O	O	O	O	O	50.32	41.41	17.67	18.03	O	O	42.89	40.82
	7	154.07	129.26	120.70	124.38	111.96	110.22	O	O	O	O	O	O	74.64	70.66	15.55	14.90	O	O	37.46	41.80
	8	126.46	111.56	122.11	121.69	99.13	107.78	O	O	O	O	O	O	74.55	76.34	21.20	21.78	O	O	45.57	43.81
	9	144.19	126.33	135.34	134.95	121.01	123.83	O	O	O	O	O	O	68.78	67.11	19.87	18.78	O	O	40.25	45.93
	10	157.32	152.48	137.87	142.73	107.94	111.74	O	O	O	O	O	O	72.06	76.74	15.40	14.96	O	O	40.96	39.89
	11	121.10	129.84	123.79	122.58	102.03	105.20	O	O	O	O	O	O	61.21	58.75	16.87	17.83	O	O	41.44	40.58
	12	131.00	141.15	141.09	135.50	111.39	119.59	O	O	O	O	O	O	68.23	63.22	18.93	19.55	O	O	40.25	38.40
	13	153.45	133.51	126.14	130.27	133.58	132.16	O	O	O	O	O	O	55.42	77.56	20.65	21.60	O	O	37.42	39.81
	14	165.50	151.31	155.52	141.29	117.68	123.61	O	O	O	O	O	O	86.81	74.50	16.59	17.32	O	O	39.18	40.07
	15	23.71	119.61	94.92	112.26	0.00	126.13	O	O	O	O	O	O	83.16	32.62	16.22	19.42	O	O	43.88	40.48
	16	129.37	139.03	122.77	116.50	104.78	106.30	O	O	O	O	O	O	79.75	71.30	15.54	17.01	O	O	39.62	40.20
	17	158.61	144.89	155.26	141.56	101.57	110.44	O	O	O	O	O	O	69.77	66.37	17.89	15.93	O	O	39.00	42.64
	18	136.03	130.41	125.94	122.55	188.66	120.39	O	O	O	O	O	O	84.74	87.50	16.45	14.88	O	O	37.94	36.43
	19	149.60	148.77	143.46	140.16	119.36	120.07	O	O	O	O	O	O	71.63	71.38	18.53	20.01	O	O	41.51	39.23
	20	158.70	148.69	141.47	133.32	121.68	116.30	O	O	O	O	O	O	79.97	84.64	21.11	19.54	O	O	45.08	45.27

Angles measured in degrees.
C8, T1, L2, and L5—binary scale: O, observed (5/5 strength); NO, not observed (3/5 strength).

some participants. These findings suggest the proposed TELE has the potential to be successfully adapted into more widespread practice based on satisfaction scores observed in our patient cohort.

There are several limitations that should be noted. First, because this was a pilot study, an *a priori* power analysis was not conducted. In addition, clinicians were not blinded to whether patients had spine disease or were healthy controls. Furthermore, the control group participants were selected from a convenience sample of health care workers, which may have skewed results due to participation/effort. Notably, achievement of peak-torque angle is a function of the TheraBand's resistance and the speed at which the participant moves through the full range of motion. A major improvement to the current protocol could be made by calculating observed peak-torque (force) for each exercise in the motor examination and correlating these values to predefined values of how much strength individuals should be able to exert based on their baseline demographics.[62,63] This would create a more nuanced motor grading scale with increased differentiation between 3/5, 4/5, and 5/5 strength. Furthermore, a graded system for the motor portion of C8, T1, L2, and L5 must be developed to replace the original binary scale incorporated in the present study; however, the same criticisms of telehealth scoring for C8 and T1 can be made of most in-person neurological examinations. Although it is possible to more precisely measure grip strength with instruments such as a dynamometer in an in-person examination, these are not routinely used in most spine

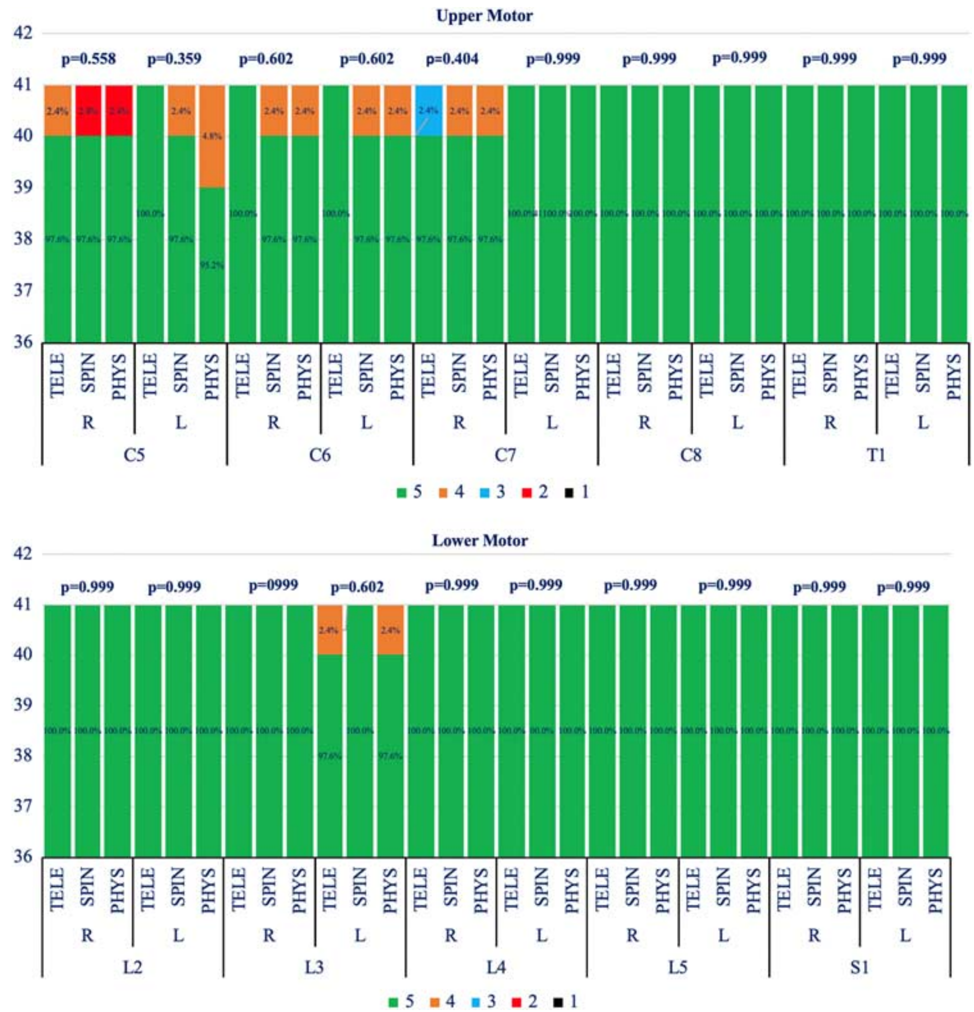

FIGURE 7. Traditional Neurological Testing versus Telemedicine Neurological Examination (Motor). full color online

practices. Performing a blinded, randomized controlled trial would provide higher quality data regarding the accuracy of testing in the telemedicine arm.

Other limitations include the fact that administration of this test required significant in-person instruction on how to use the testing tools before conducting the examination. Therefore, to conduct this examination in a remote setting, patients would need this kit of complete materials to be delivered in advance and a significant amount of time and training. This would require significant resources for coordinating logistics of delivery before the time of examination and ensuring adequate patient instruction. Indeed, technological limitations present another element of significant variability in standardizing examinations as patients may have video cameras with varying quality or angles. To accurately measures angles and qualitatively assess special tests, both upper and lower extremities need to be visualized in the field of view. This would limit participation in remote examinations if patients did not have the adequate technological hardware requirements to participate. In addition, the costs of the testing materials themselves need to be considered. On the basis of the current prices for resistance bands, SWM, and grip tools, we estimate that the price of a testing kit would cost ~$50. Including shipping and handling costs would further increase this price. Therefore, an in-depth analysis regarding optimization of costs would need to be conducted before this model is feasible. Finally, certain components of the neurological test may be unsafe to conduct remotely (eg, Romberg test, tandem gait) due to a propensity for patients to fall, or may not be feasible (deep tendon reflexes, Hoffman test, Babinski sign).

CONCLUSIONS

This pilot study's findings suggest that a comprehensive neurological spine assessment can be achieved via telemedicine for most patients. The majority of neurological testing performed by experienced clinicians may be reproduced using a self-administered testing kit. Further studies are warranted to validate these findings, as well as elucidate the benefits of this novel examination and assess the potential for its application in clinical use.

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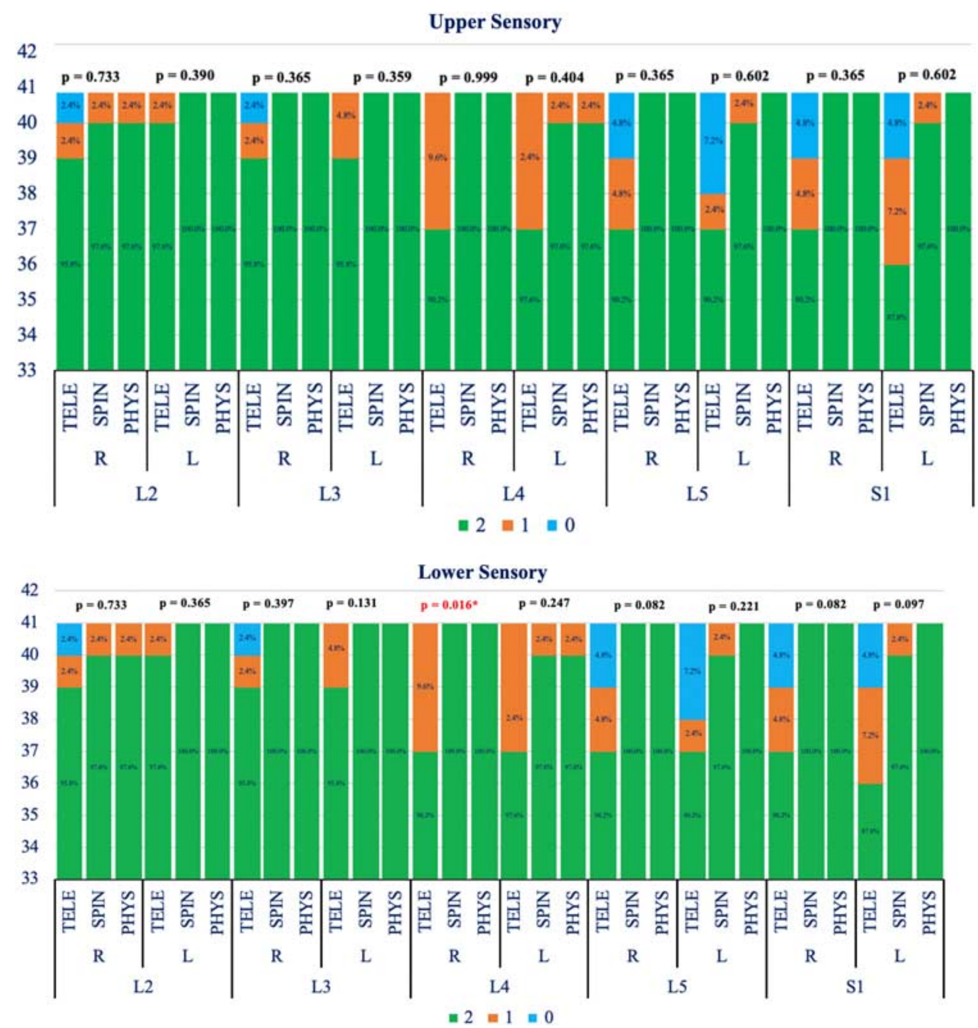

FIGURE 8. Traditional Neurological Testing versus Telemedicine Neurological Examination (Sensory). *$P < 0.05$. full color online

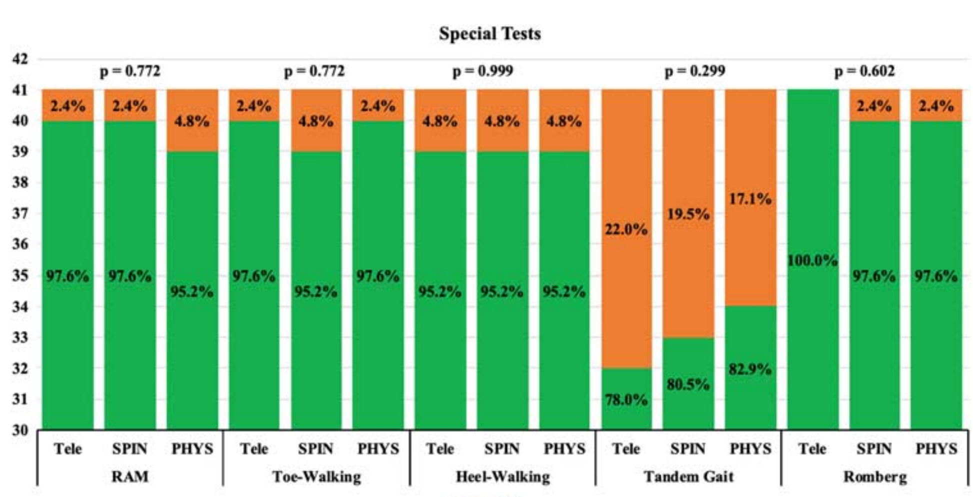

FIGURE 9. Traditional Neurological Testing versus Telemedicine Neurological Examination (Special Tests). full color online

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TABLE 9. Results From Satisfaction Survey

Group	Participant	Overall Satisfaction	Pain/Discomfort Experienced During Examination	Comments
Healthy (H)	1	Very satisfied	None	No difficulty
	2	Very satisfied	None	No difficulty
	3	Very satisfied	None	No difficulty
	4	Very satisfied	None	No difficulty
	5	Very satisfied	None	No difficulty
	6	Very satisfied	None	No difficulty
	7	Very satisfied	None	No difficulty
	8	Very satisfied	None	No difficulty
	9	Very satisfied	None	No difficulty
	10	Very satisfied	None	No difficulty
	11	Very satisfied	None	No difficulty
	12	Very satisfied	None	Ankle dorsiflexion difficult
	13	Very satisfied	None	Ankle dorsiflexion difficult
	14	Very satisfied	None	Difficulty seeing monofilament
	15	Very satisfied	None	Really enjoyed the tele-examination
	16	Very satisfied	None	Should test the EHL tendon somehow
	17	Very satisfied	None	No difficulty
	18	Very satisfied	None	Made him more mindful of his own physical capability
	19	Very satisfied	None	Saw telemedicine eye doctor and finds the project interesting
	20	Very satisfied	None	No difficulty
	21	Very satisfied	None	No difficulty
Spinal disease (D)	1	Very satisfied	None	No difficulty
	2	Very satisfied	None	Great for exercise
	3	Very satisfied	None	Ankle dorsiflexion difficult
	4	Very satisfied	None	Great experience overall
	5	Very satisfied	None	Enjoyed it as exercise therapy
	6	Very satisfied	None	No difficulty
	7	Very satisfied	None	No difficulty
	8	Somewhat satisfied	None	R shoulder limited by pain
	9	Very satisfied	None	No difficulty
	10	Very satisfied	None	Relieved the anxiety of waiting for her visit
	11	Very satisfied	None	No difficulty
	12	Neither satisfied nor dissatisfied	None	Heel-to-toe might be dangerous
	13	Very satisfied	None	No difficulty
	14	Very satisfied	None	No difficulty
	15	Somewhat satisfied	Yes—arm pain	No difficulty
	16	Very satisfied	None	No difficulty
	17	Very satisfied	None	No difficulty
	18	Very satisfied	None	No difficulty
	19	Very satisfied	None	No difficulty
	20	Very satisfied	None	No difficulty

EHL indicates extensor hallucis longus.

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