# Simple and Reliable Position Sense Assessment Under Different External Torques: Toward Developing a Post-Stroke Proprioception Evaluation Device

Kang-Won Lee, Sang Hoon Kang, *Member, IEEE*, and Soo-Chul Lim, *Member, IEEE*

***Abstract*— Evaluation of position sense post-stroke is essential for rehabilitation. Position sense may be an output of a process needing position information, external torque, and the sense of effort. Even for healthy individuals, it is unclear whether external torque affects position sense. Thus, evaluation of position sense under different external torques in clinical settings is strongly needed. However, simple devices for measuring position sense under different external torques in clinical settings are lacking. Technologically advanced devices that may evaluate the elbow position sense under different torques were reported to be infeasible clinically because of device complexity and the need for technical experts when analyzing data. To address the unmet need, in this study, a simple and light elbow position sense measurement device was developed that allows clinicians to measure elbow position sense under different external torques in the form of position matching error objectively without any technical difficulties. The feasibility of the device, including intra-session intra-rater reliability and test-retest reliability over two consecutive days, was verified to be clinically applicable using tests with 25 healthy subjects. Thanks to its ease of use, high reliability, and ease of data analysis, it is expected that the device can help to evaluate the position sense post-stroke comprehensively.**

***Index Terms*— Proprioception, proprioceptive position sense, external torque.**

Manuscript received November 8, 2021; revised March 15, 2022; accepted March 21, 2022. Date of publication March 24, 2022; date of current version April 5, 2022. This work was supported in part by the Translational Research Center for Rehabilitation Robots, Korea National Rehabilitation Center, Ministry of Health & Welfare, South Korea, under Grant NRCTR-EX17008; and in part by the Korea Medical Device Development Fund grant funded by the Korea Government (the Ministry of Science and ICT, the Ministry of Trade, Industry and Energy, the Ministry of Health & Welfare, and the Ministry of Food and Drug Safety) under Project 1711138334 (Project KMDF_PR_20200901_0165). *(Corresponding authors: Sang Hoon Kang; Soo-Chul Lim.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Institutional Review Board at Dongguk University under Application No. DUIRB-201708-10.

Kang-Won Lee and Soo-Chul Lim are with the Department of Mechanical, Robotics and Energy Engineering, Dongguk University, Seoul 04620, South Korea (e-mail: kangwon353@dongguk.edu; limsc@dongguk.edu).

Sang Hoon Kang is with the Department of Mechanical Engineering, Ulsan National Institute of Science and Technology (UNIST), Ulsan 44919, South Korea, and also with the Department of Physical Therapy and Rehabilitation Science, University of Maryland, Baltimore, MD 21201 USA (e-mail: sanghkang@unist.ac.kr).

Digital Object Identifier 10.1109/TNSRE.2022.3161948

## Nomenclature

| | |
|---|---|
| ADL | Activities of daily living |
| ANOVA | Analysis of Variance |
| CI | Confidence interval |
| CTM | Contralateral target matching |
| EExT | Extension external torque |
| EPMA | Elbow position matching accuracy |
| FExT | Flexion external torque |
| IQR | Interquartile range |
| ITM | Ipsilateral target matching |
| LoA | Limits of Agreement |
| PS | Position sense |
| STD | Standard Deviation |
| TME | Target matching error |
| ZExT | Zero external torque |

## I. Introduction

THIS paper proposes a simple and reliable elbow device that enables the evaluation of the elbow joint position sense, a sub-modality of proprioceptive sense [1], under different external torques. Proprioception is an individual's ability to have sub-modalities, including a sense of body orientation/position, body/limb motion, body segment static position, displacement, velocity, acceleration, and muscular sense of force, effort, heaviness [1], [2].

PS is defined as the sense of the static position of a joint or limb without using vision [1], [3]–[6]. PS affects the quality of movement control [7], including control of slow and goal-directed movements [8]–[10], multi-joint coordinated movements [10], [11], accurate reaching/tracking movement [12], prehension [13], and correction of ongoing movement [14]. PS is important for movement control both in feedforward (anticipation, preparation, and response planning) and feedback (adaptation and skill refinement) operations [2], [14]–[17], and also for ADL [13], [15], [18]. This may be because PS could be used for estimating position during motor planning (feedforward) [16], and is related to the ability to detect and correct errors (adaptation and skill refinement) [19]. A loss or degradation of PS may result in degrade/loss of movement control [20] because the people with lost or degraded PS must rely on visual inputs for

feedforward and feedback processes. They may have difficulties in learning novel movements, improving the quality of movement, or maintaining quality over a series of repetitions because of the absence of feedback for adaptation and skill refinement [19].

Clinically, over 60% of individuals with stroke present some form of sensory deficit [15], [21]–[24]. For those individuals, impairment in proprioception (commonly the sensing of limb position in space [7], [18]) is frequently observed [25], [26] with lesions in the brain areas – thalamus [27]–[30], posterior limb of the internal capsule [31], and somatosensory (S1) and posterior parietal cortices [31]–[33] – involved in numerous functions related to sensory processing. Damages to the supramarginal gyrus, the arcuate fasciculus, and Heschl's gyrus were associated with the persistent PS deficit at 6-month post-stroke [34]. Deficits in PS were found to be largely independent of the deficits in motor performance [6], [35]. PS is strongly associated with motor recovery [7], [36]–[38]. The degree of PS impairment is associated with the ability to self-care, the likelihood of being discharged to one's home, and the period of rehabilitation [7], [39]–[43]. Thus, an assessment of PS is essential for treatment planning, carrying out progress reviews, diagnosis, discharge planning, and prognosis of individuals with stroke [44]. Moreover, as is the case of healthy individuals (the force-movement illusion) [1], [45]–[49], because post-stroke PS may be affected by external forces/torques that could be encountered during ADL tasks, an investigation of the alteration in the post-stroke PS may allow us to understand the underlying mechanism better, and may assist/complement the clinical assessment. Most clinical assessments, however, rely on categorical or ordinal ratings by clinicians displaying very poor inter-rater reliability and sensitivity, poor or absent normal value criteria, or ceiling effect [18], [50]–[53], and they scarcely provide us a way to evaluate alteration in post-stroke PS under external forces/torques. There is, therefore, a strong need for an objective and reliable assessment of the post-stroke PS under different external loads for routine clinical use.

For many ADL tasks, external forces/torques may be applied to the limbs by external dynamics. For instance, one can grasp a cup of coffee and bring it to her/his mouth to drink regardless of how much coffee is in it; one can move her/his arm to the desired position without looking at it under the downward gravitational force; and one can lift a book that s/he wants to read to the vicinity of her/his face. For these tasks, in the processing of the PS, external force/torque information, obtained from peripheral proprioceptors (e.g., Golgi tendon organ), may be used [1], [45]–[49], [54]–[60] in addition to the position information from the proprioceptors in muscle, skin, and joint. Furthermore, the PS is determined not only by the afferent feedback from the muscle, joint, and cutaneous proprioceptors but also by the efferent motor commands to the muscle (effort-based signal) [1], [2], [49], which are closely related to the sense of effort [1], [61]–[63] and provide an estimate of the intended posture [2], [56], [64], [65]. The efference copy (a signal derived from the motor command) could be utilized to estimate limb states (e.g., the position and velocity) together with the limb dynamics and afferent proprioceptor signals (e.g., joint angles and external torques) [1], [63], [66]–[70]. PS might be the output from the state estimation process utilizing an internal forward model that may be located in the cerebellum [66]–[69] and/or parietal cortex [71], [72]. Even for healthy subjects, it is, however, not very clear whether or not the external forces/torques affect the PS. Some studies report significant effects of the external forces/torques [1], [45]–[49], while others do not [54]–[60]. Thus, there is a need for further investigation into the effect of external forces/torques on PS, considering that external forces/torques can change the effort command to the muscle and may be utilized together with position information to obtain PS.

The aforementioned unmet needs (i.e., need for further investigation of the effect of external forces/torques on the PS and an objective and reliable assessment of the post-stroke PS under different external torques) may be addressed using existing devices. Many devices – manual devices [60], [73], a pair of manipulanda driven by servo motors [74], and a manipulandum actuated by a hydraulic cylinder [75] – have been utilized to assess the PS under zero external torque. Many technologically advanced upper-limb rehabilitation exoskeleton robots [76] may have sufficient potential to assess elbow PS under different external torques However, the previously used technically advanced devices (e.g. the pair of manipulanda) were evaluated to be clinically infeasible because of the complexity of the equipment and the need for technical experts to perform data analysis [2], indicating a pressing need for a clinically applicable simple PS evaluation device providing different external torques

Therefore, to address the unmet needs, the goal of this study was to develop a simple elbow device, which can provide different levels of external torque, evaluate the elbow PS conveniently and reliably without technical difficulties, and be routinely used in clinics with a simple operation of the device. It should be noted that this study does not aim to develop a technically advanced device. To test the device's feasibility, an evaluation was performed on healthy subjects to determine the intra-rater reliability for measures made within a session and test-retest reliability between two consecutive measures that were 24-hours apart. Then, the effects of external torques on the elbow PS were investigated for different types of tests.

## II. Methods

### A. Simple Elbow Device for Assessing Position Sense Under Different External Torques

A simple elbow device was developed (Fig. 1) to assist clinicians in assessing post-stroke elbow PS objectively and reliably under different external torques. For the assessment, the subject sat upright comfortably on a chair. The upper arm of the subject was supported by a sturdy stand, connected to the upper arm link of the device, from below at 80° shoulder flexion. The forearm of the subject was strapped to lightweight carbon fiber braces fixed to the forearm link of the device while aligning the subject's elbow joint axis with the device's mechanical axis. The upper arm link could be adjusted along

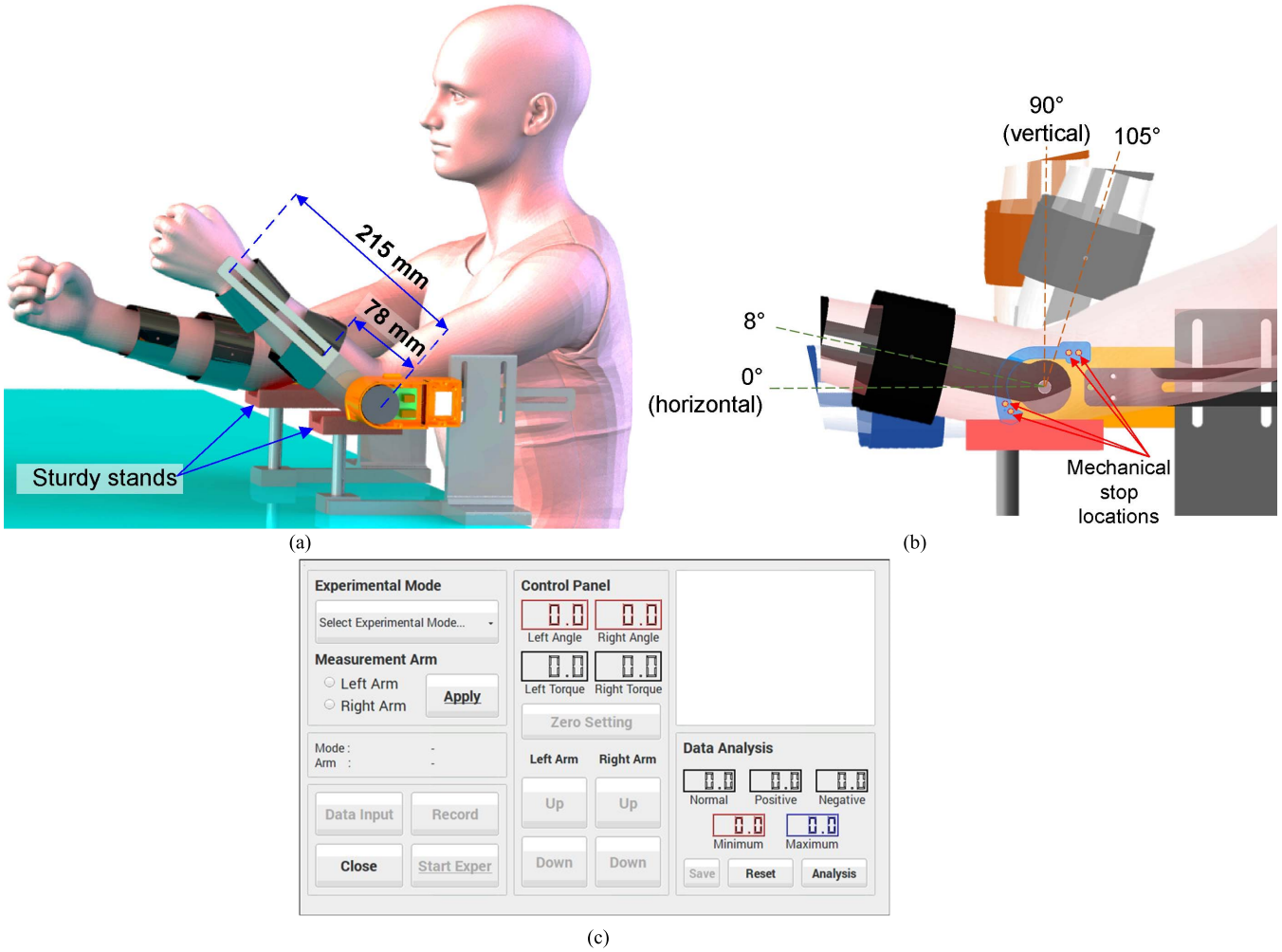


Fig. 1. The developed elbow device for assessing elbow position sense under different external torques. (a) A subject is wearing the elbow device on both of his arms. The forearm braces can be adjusted along the long axis of the forearm link. (b) Mechanical stops can be placed conveniently for safety. (c) Touchscreen display of the Raspberry Pi 3b control box allowing clinicians to conveniently select the type of a test and the external torque level and to read the elbow joint angle in real-time. The type of the test can be selected from the experimental mode menu. An indicator arm can be chosen from the measurement arm menu. The external torque can be changed by touching the 'up' or 'down' button under both the left arm and right arm.

the anteroposterior direction to match the elbow joint flexion-extension axis and the device's flexion-extension mechanical axis. The location of forearm braces can also be adjusted along the forearm link direction to accommodate subjects with different arm lengths. The device might be portable in the clinical setting because of its lightweight (0.57 kg). Because of the lightweight design, the forearm link weighted 0.14 kg, its inertia was 0.002 kg·m$^2$, and the distance of the center of mass from the elbow joint was 0.095 m.

The device was able to exert a range of external torques to the subject's elbow in addition to the naturally existing gravitational torque due to the forearm and hand. Hereafter, external torque means the torque exerted to the elbow joint actively by the proposed device. The capable range of external torque was set to be from 1.33 Nm flexion torque to 1.33Nm extension torque in the custom software developed for the PS sensing. This external torque was provided in a feedforward manner with the identified voltage-to-torque relationship (see sections II.C.1) and III-A) using a flat DC motor (EC45 flat, Maxon Motor, Switzerland) with a built-in encoder and 47:1 low-noise spur gear system (Maxon Motor, Switzerland). Considering that the long-term goal of the device is to assist the evaluation of the elbow PS of individuals with stroke, the maximum torque magnitude (1.33Nm) that the device can exert on the subjects was determined to be lower than the minimum of the maximum torques reported in previous elbow PS studies with unimpaired subjects: 1.47 – 2.60Nm (0.6 – 1.06 kg force at the wrist) [45], maximum of 6.13 Nm (2.5 kg force at the wrist) [46], 4.9 – 12.25Nm (10% – 25% of maximum voluntary contraction [48]). Because most of the studies provided forces around the wrist joint, the forces and weights reported were converted to equivalent torques assuming that the forces were applied at the distal end of a 0.25 m forearm orthogonally. When one with a forearm length of 0.25 m holds a light and empty cup (0.35 kg), the torque exerted to the elbow is an extension torque of ∼0.86Nm (65% of 1.33Nm), which can be experienced in daily life even for individuals with stroke.

Further, the device could rotate the subject's elbow passively to a target location because the device can be in position control mode using a built-in proportional-derivative control (EPOS4, Maxon Motor, Switzerland). One could change the external torque level by simply touching the control box's touch screen display (Raspberry Pi 3b; Fig. 1(c)). The torque was provided as a step function of time. The motor was controlled at a sampling rate of 200Hz, and the elbow joint angle was measured with a resolution of 0.088°. The external torque level and elbow joint angle were displayed on the control box's touch screen with an update rate of 60Hz. The device's range of movement could be adjusted for safety with mechanical stops (Fig. 1(b)). The motor torque was limited with the real-time monitoring of a motor current. Enable switches, which could stop the device in no time, were given to both the clinician and the subject. Note that because the maximum torque that the device could generate was 3.1 Nm in the flexion and extension directions one could increase the maximum torque by modifying both the custom software and the current limit of the real-time motor current monitoring, if needed.

Commonly adopted PS tests, namely ITM [54], [55], [74], [77]–[82] and CTM [1], [48], [60], [70], [73], [83]–[86] tests, were considered for testing PS in this study. ITM tests and CTM tests with different levels of external torque could be performed with the developed device as follows.

*1) Ipsilateral Target Matching Test:* This test is a one-arm test. The subject wore the device on the test arm. The subject flexed and extended her/his elbow joint of the test arm several times with wearing the device and was blindfolded. A clinician then manually rotated the elbow joint to a target angle of 40°−50° [70] elbow flexion while the subject was relaxing, and the elbow joint stayed at the target angle for approximately three seconds to allow the subject to remember the target angle by solely relying on her/his PS. After staying at the target angle, the subject returned the elbow to the initial posture voluntarily, immediately after hearing the verbal cue from the clinician who measured the three-second elapsed time. During the process, the device generated zero external torque. The subject was then asked to match the perceived angle by solely relying on her/his PS under the selected level of external torques provided by the device in a feedforward manner. Once the subject felt that the elbow joint had reached the target angle, the elbow angle (named as the re-created angle) was maintained, and the end of the matching trial was verbally expressed. The clinician pressed the saving button to record the target matching error (= target angle − re-created angle), representing the position matching accuracy [1], [48], [73], [85], [86] in this study. During the matching process, the subject was instructed not to rush but to move the elbow joint to the perceived target joint angle [85]. For individuals with stroke, this instruction is expected to help to prevent spasticity. At the end of each trial, the elbow joint was moved back to the initial resting position. A fully extended elbow angle was defined as 0° flexion, and as the elbow flexed, the elbow angle increased. Thus, a positive matching error means that the elbow stopped at a more extended angle than the target angle at a trial (i.e., re-created angle < target angle) [1], [48], [73], [85], [86].

*2) Contralateral Target Matching Test:* This test is a two-arm test. The subject wore a pair of the device on both arms. The elbow joint of the reference arm (i.e., the arm that was placed at the target angle [1], [48], [73], [85], [86]) was flexed and extended several times by the device, and the subject was blindfolded. A clinician then rotated the reference arm's elbow joint to a target angle of 45−55° elbow flexion [70] using the device under the position control while the subject was relaxing, and the elbow joint of the reference arm remained at the target location. Once the elbow joint of the reference arm reached the target position, the subject matched the elbow angle of the indicator arm (i.e., the arm moved by the subject to match the reference arm angle [1], [48], [73], [85], [86]) to the perceived angle of the reference arm as closely as possible without rushing under a selected level of external torques [85]. As soon as the subject verbally expressed the end of a matching trial, the clinician recorded the matching error by pressing the saving button while the subject maintained the indicator arm's elbow angle. After completing the trial, the elbow joint of the reference arm was again flexed and extended several times by the device and returned to the target position. Then, the elbow joint of the indicator arm moved back to the initial resting position for the subsequent trial. Similar to the ITM test, the matching error was defined as the difference between the target angle reached by the reference arm and the re-created angle reached by the indicator arm (= target angle – re-created angle).

For both ipsilateral and contralateral tests, upper arm movements were monitored to disregard data accompanying the significant upper arm movements.

## B. Subjects

A group of 25 healthy subjects with no previous history of musculoskeletal injury and neurological impairment was recruited for this study. The Institutional Review Board at Dongguk University reviewed and exempted this study and waived the requirement for written informed consent.

## C. Experimental Procedure

*1) Identification of the Current-Torque Relationship of the Device:* By attaching a force sensor at the distal end of the forearm link, the relationship between the current applied to the motor and torque generated at the elbow joint of the device was obtained by applying ten different currents to the motor while measuring the torque at the elbow joint of the device. The elbow joint torque was computed as the multiplication of the force measured from the force sensor and the forearm link's length.

*2) Reliability Test:* To quantify intra-rater reliability for the data obtained within the same session on the same day, an ITM test was performed with both the preferred and non-preferred arms under three different levels of external torque: 0.86 Nm FExT (0.86 Nm), ZExT (0 Nm), and 0.86 Nm EExT (−0.86 Nm). For the same subjects, the CTM test was also performed under the same three different external torques with the preferred arm as the indicator arm and the nonpreferred

arm as the reference arm. Five trials were conducted for each test with adequate rest in between.

To quantify the test-retest reliability, the elbow PS of the ten subjects (5M/5F), who were able to participate in the study for two consecutive days, among the 25 subjects was evaluated twice with a 24-hours interval in between. Each day, the ITM test was performed with the subjects' preferred arm under ZExT, and the CTM test was performed with the preferred arm as the indicator arm under the three different levels of external torque. For a potential comparison with the PS of individuals with stroke, the preferred arm – reported to have less sensitive PS than that of the nonpreferred arm [74], [77]–[79] – was selected as the indicator arm. Five replicated TME were obtained for each subject on each occasion, with adequate rest in between.

### D. Data Analysis

*1) Device Characteristics:* Linear regression was performed to determine the relationship between the motor current and the device's external torque. The slope of the current−torque curve was obtained, and the goodness-of-fit was verified using $R^2$.

To quantify the variation in the torque provided during the test, the maximum inertial and gravitational torques due to the link were obtained with the elbow angle and angular acceleration while the subject voluntarily moved one's forearm during the tests. Moreover, the inertial torque due to forearm and hand were obtained with the aforementioned elbow angular acceleration and the inertia estimated based on anthropometry [87].

*2) Reliability Test:* Widely adopted [88] reliability measures [89]–[94] – the repeatability coefficient for intra-rater reliability and LoA for test-retest reliability – were used considering their simplicity and ease of use.

The repeatability coefficient [90], [92]–[94] was obtained from five replicates of the TMEs of the subjects to quantify the limits within which 95% of differences between the two replicates of TME (obtained within a session on the same day using the same device) lie. The repeatability coefficient was obtained as the 2.77 times the within-subject STD (i.e., the STD of the measurement errors) obtained from a one-way ANOVA of the five replicates with subjects as the factor by following [90], [92]–[94] for each external torque level (ZExT, FExT, and EExT) and each type of matching test (ITM with preferred arm, ITM with nonpreferred arm, and CTM).

For the rest of the analysis, the mean of five replicated TMEs obtained under each external torque condition for each type of test was computed and defined as the EPMA.

To quantify the test-retest reliability, the EPMA of each of the ten subjects was obtained daily for each test. The LoA and bias were then obtained from the EPMA of the two consecutive days for each external torque condition and each type of matching test [89]–[93].

*3) Effect of External Torque on the Position Sense:* A two-way repeated measure ANOVA was used to test the effect of external torque levels (ZExT, FExT, and EExT) and types of test (ITM with preferred arm, ITM with nonpreferred arm, CTM with the preferred arm as the indicator arm) on the EPMA. A one-way repeated measure ANOVA was performed if significant interactions between the two factors were detected, followed by pair-wise comparisons with adjusting $p$-values based on the Holm-Bonferroni method. Adjustments were made if a violation of sphericity was found (Huynh-Feldt adjustment if the sphericity estimate $>0.75$, Greenhouse-Geisser otherwise).

To provide healthy young individuals' PS as baseline data, median, quartiles, 2.5$^{th}$ and 97.5$^{th}$ percentiles, minimum, maximum, and IQR of PS were obtained for each external torque level and each type of matching test [7], [95], [96].

For all statistical tests in this study, the significance level was set at 0.05.

TABLE I
REPEATABILITY COEFFICIENT FOR SINGLE MEASUREMENT (N=25 SUBJECTS)

| | Ipsilateral matching test | | Contralateral matching test[a] |
|---|---|---|---|
| | Preferred arm (10R/15L) | Nonpreferred arm (15R/10L) | |
| ZExT | 8.6° | 9.5° | 7.9° |
| FExT | 7.5° | 8.4° | 8.2° |
| EExT | 7.3° | 7.0° | 7.0° |

[a]Indicator arm was the preferred arm (10R/15L).

## III. RESULTS

The subjects were 25.3 ± 1.6 (mean ± STD) years old. Sixteen subjects were male, and nine were female. For ten subjects, their preferred arm was the right arm, and for the rest, the left arm was the preferred arm. For all tests, no significant upper arm movements were observed.

### A. The Device's Characteristics

The current-to-torque constant of the device was found to be 3.28 Nm/A, with an $R^2$ of 99.98%. Thus, using the current-to-torque constant, different external torques were applied to the subject's elbow in a feedforward manner.

The torque variation during the tests was quantified. The maximum gravitational torque due to the link was 0.130 Nm in the extension (i.e., −0.130Nm). The maximum angular acceleration was ∼2 rad/s$^2$ across all subjects. Thus, the maximum inertial torque due to the forearm link was 0.004 Nm in both flexion and extension. In total, the maximum torque contribution due to the link was 0.134 Nm in the extension (i.e., −0.134Nm). The maximum inertial torque due to the forearm and hand was 0.10 Nm in both flexion and extension.

### B. Reliability

*1) Intra-Rater Reliability (Within a Session on the Same Day Using the Same Device):* The repeatability coefficient under different external torque levels (ZExT, FExT, and EExT) and test types (ITM with preferred arm, ITM with nonpreferred arm, CTM with the preferred arm as the indicator arm) were found (Table I).

TABLE II
TEST-RETEST(DAY-TO-DAY) BIAS AND LIMITS OF AGREEMENT. MEAN (95% CI) (N=10 SUBJECTS)

| | | Bias | Limits of Agreement | |
|---|---|---|---|---|
| | | | Lower limit | Upper limit |
| Contralateral matching test[a] | ZExT | −1.0° (−2.9°, 0.8°) | -6.1° (−9.0°, −3.3°) | 4.1° (1.2°, 6.9°) |
| | FExT | −0.7° (−1.6°, 0.3°) | −3.3° (−4.7°, −1.8°) | 1.9° (0.5°,3.4°) |
| | EExT | 0.8° (−1.1°, 2.6°) | −4.4° (−7.3°, −1.5°) | 5.9° (3.0°,8.8°) |
| Ipsilateral matching test[b] | ZExT | −0.3° (−1.6°, 0.9°) | −3.7° (−5.6°, −1.8°) | 3.0° (1.1°, 4.9°) |

[a]Indicator arm was the preferred arm. [b]Tested arm was the preferred arm.

*2) Test-Retest Reliability (Day-to-Day):* The LoA and bias for each external torque level and each test type were obtained (Table II). From the 95% CI of each of the biases, it was found that there was no significant bias under all tested conditions.

### C. Effect of External Torques on the Elbow Position Sense

The summary of EPMA for each test under each external torque was obtained (Table III). The effect of the external torque and test type on the elbow PS was found (Fig. 2). There was a significant interaction between external torque levels and test type ($F_{(4,96)} = 10.068$; $p < 0.001$). A significant difference in EPMA between external torque levels was found with a one-way repeated measure ANOVA for the CTM test ($F_{(2,48)} = 13.166$; $p < 0.001$) and for the ITM test with nonpreferred arm ($F_{(2,48)} = 5.858$; $p = 0.005$). A significant difference was found in the EPMA between the test types using a one-way repeated measure ANOVA for the matching test under the EExT ($F_{(1.265,30.365)} = 9.880$; $p = 0.002$). In the case of CTM, the EPMA (mean ± STD: $-0.3° \pm 4.0°$) under ZExT was significantly higher than that ($3.3° \pm 5.1°$) under the EExT ($p < 0.001$), and the EPMA ($0.9° \pm 4.5°$) under the FExT was significantly higher than that under the EExT ($p = 0.014$). The re-created angle obtained under the EExT was smaller than that under the FExT (mean difference ± 95% CI: $-2.5 \pm 1.7°$) and that under the ZExT (mean difference ± 95% CI: $-3.7 \pm 1.4°$) for the CTM test. In the case of the ITM test with the nonpreferred arm, the EPMA (mean ± STD: $0.8° \pm 2.1°$) under ZExT was significantly lower than that ($-0.3° \pm 1.7°$) under the external flexion torque ($p = 0.010$). For the nonpreferred arm ITM test, the re-created angle obtained under the ZExT was located at a more extended position than that under the FExT (mean difference ± 95% CI: $-1.1 \pm 0.7°$) significantly. For tests under the EExT, the EPMA from the CTM test (mean ± STD: $3.3° \pm 5.1°$) was significantly lower than that ($0.3° \pm 2.0°$) from the preferred arm ITM test ($p = 0.012$) and that ($0.0° \pm 1.8°$) from the nonpreferred arm ITM test ($p = 0.005$).

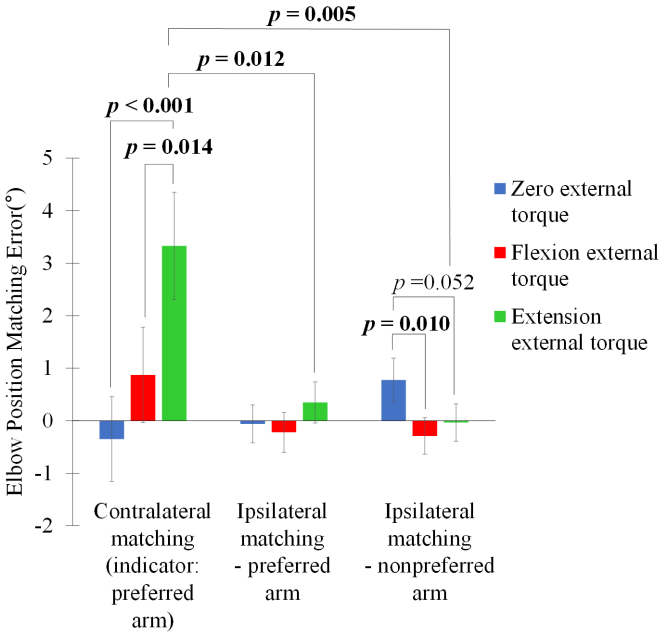


Fig. 2. Target matching error with three different external torque levels and three types of test (n=25). Vertical error bars represent ±1 standard error about each mean across subjects.

## IV. DISCUSSION

In response to strong clinical and research needs, a device that enables us to assess the elbow PS under different external torques was developed for the first time, and its feasibility, including the reliability, was verified. The device was able to generate many different external torques, which were not easy to realize in clinical tests, and required only a short time (<5 minutes) for subjects' wearing. During the test, clinicians can easily change the external torque level by simply touching the device's control panel and can read and save the angle from the display without any further processing. Surely, for convenient post-processing, the data can also be saved in an electronic device, including computers. Thus, the proposed device has good potential for use in clinical settings.

### A. Position Sense Evaluation Devices

As mentioned in section I, many devices [60], [73], including technically advanced robots [74], [75] could be utilized for the measurement of the elbow PS However, even with the advancement in technology, those devices [74] were not clinically feasible because of the complexity of the equipment and the need for technical experts to provide data analysis [2].

The operation of the proposed device was made very simple considering the clinicians' convenience It took only a few minutes for the subject to wear the device. With a few touches to the control panel, clinicians can get all the information they need without the technical difficulties they may face. The elbow joint angle and the external torque provided are displayed in real-time and the external torque can be changed with just one touch of the panel. Thus, compared with the previous devices that have been developed, the proposed device is much less complex in terms of device operation.

TABLE III
SUMMARY OF ELBOW POSITION MATCHING ACCURACY UNDER DIFFERENT EXTERNAL TORQUE (N=25 SUBJECTS)

| | | Minimum | **2.5th Percentile** | Lower quartile | **Median** | Upper quartile | **97.5th Percentile** | Maximum | IQR |
|---|---|---|---|---|---|---|---|---|---|
| Contralateral matching test[a] | ZExT | -6.8° | **-6.8°** | -2.4° | **-0.8°** | 1.4° | **10.1°** | 10.5° | 3.8° |
| | FExT | -7.5° | **-7.5°** | -2.2° | **1.2°** | 2.6° | **9.6°** | 9.6° | 4.8° |
| | EExT | -4.1° | **-4.1°** | 0.2° | **2.2°** | 7.9° | **15.6°** | 16.2° | 7.7° |
| Ipsilateral matching test (preferred arm, 10R/15L) | ZExT | -5.7° | **-5.3°** | -1.0° | **0.1°** | 1.3° | **3.0°** | 3.1° | 2.3° |
| | FExT | -4.0° | **-3.9°** | -1.3° | **-0.5°** | 0.7° | **4.7°** | 5.0° | 2.0° |
| | EExT | -2.8° | **-2.7°** | -0.9° | **0.4°** | 1.0° | **5.7°** | 5.8° | 1.8° |
| Ipsilateral matching test (non-preferred arm, 15R/10L) | ZExT | -2.6° | **-2.5°** | -0.7° | **0.7°** | 1.7° | **6.4°** | 6.8° | 2.4° |
| | FExT | -4.2° | **-4.0°** | -1.6° | **0.0°** | 0.5° | **3.1°** | 3.2° | 2.1° |
| | EExT | -3.5° | **-3.5°** | -1.0° | **0.0°** | 0.8° | **3.8°** | 3.9° | 1.8° |

[a]Indicator arm was the preferred arm.

Further, because the angle can be directly read from the display and saved in the device with just one click, there is no need for technical experts to provide data analysis Thus, the practical *advantages* of the device are that it is easy for clinicians to operate, and no technical experts are needed to analyze the data obtained. Clinically available isokinetic dynamometers (e.g., Biodex) may provide isotonic mode, indicating the potential for evaluating elbow PS under different external torques. However, those devices were not specifically designed for the elbow PS evaluation are heavier and occupy larger space than the proposed device due to the large motor and the controller (i.e., not portable). Moreover, the interface and operation of those dynamometers may not be simple compared with the proposed device.

The maximum torque variation due to the forearm link was 0.134 Nm, indicating that the effect of forearm link inertia and mass on the test was minimal. For an individual with a forearm length of 0.25 m to hold a 0.5 kg object, 0.134 Nm is needed. An alkaline AA battery weighs 0.23 kg. The maximum torque variation due to the forearm and hand was 0.10 Nm, which was obtained with the maximum acceleration from the subjects, indicating a non-zero inertial torque due to the forearm and hand. However, the maximum inertial torque due to the forearm and hand was equivalent to holding less than two AA batteries, which is much lighter than smartphones (∼0.2 kg) being used for evaluating PS [97] Since individuals with stroke may be slower than the healthy subjects, the inertial torque contribution is expected to be smaller for individuals with stroke.

For each trial, since the net torque acting on the forearm initially accelerated the forearm toward the target angle, it generated energy. Later, the net torque decelerated the forearm near the target angle, indicating that it absorbed/dissipated energy. Because of the small magnitude of the external torque, the net muscle torque exerted on the elbow was always the flexion torque to overcome the gravitational torque due to the forearm and hand at least partially.

## B. Feasibility of the Elbow Device

*1) Reliability:* First, the intra-rater reliability (within a session) was evaluated by computing the repeatability coefficients. The repeatability coefficients were smaller than the previously reported differences in the replicated TMEs (>10°) of individual subjects [85], [86], indicating that the variability in the replicates of the TME was well controlled within an acceptable range and was maybe mostly due to intra-individual variability. Although not large, to reduce this within-session variability, the mean of five replicates of each subject's TME was used for subsequent analyses to represent the accuracy of elbow position matching of each subject [92]

Second, the test-retest reliability (day-to-day) was verified using the LoA and bias. The biases obtained from two consecutive days were not significantly different from 0°, indicating that the EPMA evaluated on two different days was not significantly different. With the LoAs obtained (Table III), it can be inferred that there is a significant change in the elbow PS if the difference between the subject's current EPMA and the previously measured EPMA is outside the LoA Among the LoAs, the lower limit of the CTM test under the ZExT had the largest magnitude (6.1°). Previous studies on post-stroke proprioceptive training reported a 10°-20° improvement in the wrist position matching accuracy (i.e., reduction in position matching error) [98] Further, the mean TME of the wrist poststroke was larger than 11° for many individuals with stroke and it even reached 53° [99] Thus, the LoAs from the test-retest reliability of the proposed device may be clinically acceptable. However, the clinical decision pertaining to the acceptability of the LoA may require further study with individuals with stroke

*2) Target Matching Errors of Healthy Young Individuals:* First, for all three test types, the differences between the previously reported TMEs [80] and the corresponding TMEs measured with the device developed in this study (Fig. 2) under the ZExT were smaller than the corresponding standard errors in [80]

Second, the external torque significantly affected the EPMA for the CTM test and the nonpreferred arm ITM test (Fig.2) with a similar trend of matching errors in the case of the CTM test when compared with those of previous studies, namely CTM test studies [60] (utilizing constant force) and [45] (utilizing variable force). The re-created angle obtained under the EExT was located at a more extended position than that

obtained under the FExT and that under the ZExT This result is consistent with the reported trend of the matching error of the studies on the CTM tests under the external torques/forces [45], [60] Thus, the external torque affected the elbow PS for the CTM test, and the results agreed well with the previous results. The differences among different external torque conditions in EPMA of the nonpreferred arm ITM tests may be considered small compared with the differences obtained in the CTM test. The external torque did not significantly affect the EPMA found in the preferred arm ITM test. Considering the subtle differences in EPMA of ITM tests the magnitude of the external torques – which is equivalent to the torque required to hold an empty cup (0.86 Nm) – might be a marginal value to affect the elbow PS of healthy young (age: 25.3 $\pm$ 1.6 years) subjects compared with the larger torque of the previous studies [45], [46], [48].

Third, the effect of the external torque on the elbow PS was more pronounced in CTM than in ITM tests, as reported in [77]. Elbow position sense studies have reported that the CTM is more difficult than the ITM because of the commonly reported demanding cognitive load involving the greater interhemispheric transfer of proprioceptive information [34], [35], [77], [80]–[82], [100], [101] though the ITM requires memory demand, unlike CTM [77]. Interhemispheric transfer of proprioceptive information may be summarized as follows [77], [81]: first, a reference (e.g., right) elbow PS information was delivered to the primary somatosensory region of the cerebral cortex in the contralateral (e.g., left) hemisphere Then the information crosses the longitudinal fissure (hemispheric divide) maybe through the transcallosal pathways of the corpus callosum [81] Eventually, the information is delivered to the ipsilateral (e.g., right) hemisphere controlling the contralateral (e.g., left) indicator elbow. In this study the effect of the external torque on the elbow PS was also evident for the CTM test. Moreover, the EPMA of the CTM test was significantly lower than that obtained from the ITM tests with both the preferred and nonpreferred arms under the EExT (Fig. 2), indicating the effect of the increased difficulty on the elbow PS. On the other hand, as discussed, in the ITM, even with the involvement of memory [77], the effect of the external torques on the elbow PS was insignificant in many cases. In other cases, the difference due to the changes in external torque was small and might be clinically insignificant. These may indicate the robustness of the PS of healthy young individuals to an external torque with a magnitude used in this study

Fourth, for the healthy young individuals, there was no difference between the accuracy of the elbow position matching of the preferred arm and that of the nonpreferred arm for the ITM test (Fig.2), indicating there was no limb preference. This is in contrast to the results presented in studies reporting higher sensitivity with the nonpreferred arm [74], [77]–[79]. This might be due to the difference in the upper limb posture and target angle between studies [74], [77]–[79], the difference in the plane of forearm movement, and the level of difficulty of the testing condition. In previous studies, the forearm moved in the horizontal plane with 70°-80° upper arm abduction excluding the effect of gravity [74], [77]–[79] Further, in [74], [79], it was reported that the preference was most pronounced in more demanding testing conditions (e.g., CTM test) than in the relatively less demanding ones (ITM test) for healthy individuals.

### C. The Benefit of Clinical Staff and Patients

The reliability of the device and method were verified in the healthy individuals (Table I and II). Moreover, the baseline data of healthy young individuals are provided (Table III). This baseline data may allow us to have a relative measure of impairment in PS post-stroke. For instance, if the EPMA of an individual with stroke is outside of the range of the $2.5^{th}$ to the $97.5^{th}$ percentile of the healthy young individuals' PS and there are no other confounding factors (e.g., age), the elbow PS of the individual with stroke may be assessed to be impaired [7], [95], [96].

Clinicians need to touch the control panel few times for the operation of the device. The data is displayed on the screen and can be saved on an electronic device, if needed, for the analysis with any of the clinician's preferred methods. Thus, the measurement of the elbow PS under different torque conditions using the developed device is expected to benefit both clinicians and patients by providing a comprehensive understanding of changes in the patients' elbow PS under external torque, facilitating patient-specific rehabilitation.

### D. Study Limitations

The proposed device, which is the first device for assessing joint PS under different external torques, is, in its current form, only for the elbow PS evaluation. Evaluation of single joint PS was performed in many clinical proprioception studies (see [77] and the references therein) at the level of consciousness [6]. This type of PS evaluation allows us a direct evaluation of joint-level impairment. Especially, joint level impairment under different external torques can be evaluated with the proposed device. Since the device is simple, the device is expected to be also used for other joints with minor modifications.

Further studies are urgently needed to investigate the PS following stroke under different external torques with an age-matched control group Testing of association between clinical proprioception measures and the EPMA from the proposed device would be valuable in further validating the utility of the device.

## REFERENCES

[1] U. Proske and S. C. Gandevia, "The proprioceptive senses: Their roles in signaling body shape, body position and movement, and muscle force," *Physiolog. Rev.*, vol. 92, no. 4, pp. 1651–1697, 2012.
[2] S. Hillier, M. Immink, and D. Thewlis, "Assessing proprioception: A systematic review of possibilities," *Neurorehabil. Neural Repair*, vol. 29, pp. 27–39, Nov. 2015.
[3] S. P. Dukelow *et al.*, "Quantitative assessment of limb position sense following stroke," *Neurorehabil. Neural Repair*, vol. 24, no. 2, pp. 178–187, Feb. 2010.
[4] J. A. Semrau, T. M. Herter, S. H. Scott, and S. P. Dukelow, "Robotic identification of kinesthetic deficits after stroke," *Stroke*, vol. 44, no. 12, pp. 3414–3421, 2013.
[5] J. M. Kenzie *et al.*, "Localization of impaired kinesthetic processing post-stroke," *Frontiers Hum. Neurosci.*, vol. 10, p. 505, Oct. 2016.

[6] S. E. Findlater and S. P. Dukelow, "Upper extremity proprioception after stroke: Bridging the gap between neuroscience and rehabilitation," *J. Motor Behav.*, vol. 49, no. 1, pp. 27–34, Jan. 2017.

[7] L. M. Carey, L. E. Oke, and T. A. Matyas, "Impaired limb position sense after stroke: A quantitative test for clinical use," *Arch. Phys. Med. Rehabil.*, vol. 77, no. 12, pp. 1271–1278, Dec. 1996.

[8] D. I. McCloskey, "Kinesthetic sensibility," *Physiol. Rev.*, vol. 58, no. 4, pp. 763–820, Oct. 1978.

[9] C. Redon, L. Hay, and J.-L. Velay, "Proprioceptive control of goal-directed movements in man, studied by means of vibratory muscle tendon stimulation," *J. Motor Behav.*, vol. 23, no. 2, pp. 101–108, Jun. 1991.

[10] J. C. Rothwell, M. M. Traub, B. L. Day, J. A. Obeso, P. K. Thomas, and C. D. Marsden, "Manual motor performance in a deafferented man," *Brain*, vol. 105, no. 3, pp. 515–542, 1982.

[11] P. J. Cordo, "Kinesthetic control of a multijoint movement sequence," *J. Neurophysiol.*, vol. 63, no. 1, pp. 161–172, Jan. 1990.

[12] M. Nagaoka and R. Tanaka, "Contribution of kinesthesia on human visuomotor elbow tracking movements," *Neurosci. Lett.*, vol. 26, no. 3, pp. 245–249, Nov. 1981.

[13] M. Gentilucci, I. Toni, S. Chieffi, and G. Pavesi, "The role of proprioception in the control of prehension movements: A kinematic study in a peripherally deafferented patient and in normal subjects," *Exp. Brain Res.*, vol. 99, no. 3, pp. 483–500, 1994.

[14] Z. Hasan, "Role of proprioceptors in neural control," *Current Opinion Neurobiol.*, vol. 2, no. 6, pp. 824–829, Dec. 1992.

[15] M. D. Rinderknecht *et al.*, "Reliability, validity, and clinical feasibility of a rapid and objective assessment of post-stroke deficits in hand proprioception," *J. Neuroeng. Rehabil.*, vol. 15, no. 1, p. 47, Dec. 2018.

[16] S. J. Sober and P. N. Sabes, "Multisensory integration during motor planning," *J. Neurosci.*, vol. 23, no. 18, pp. 6982–6992, Aug. 2003.

[17] A. J. Butler *et al.*, "Neural mechanisms underlying reaching for remembered targets cued kinesthetically or visually in left or right hemispace," *Hum. Brain Mapping*, vol. 21, no. 3, pp. 165–177, 2004.

[18] L. M. Carey, "Somatosensory loss after stroke," *Crit. Rev. Phys. Rehabil. Med.*, vol. 7, no. 1, pp. 51–91, 1995.

[19] A. Shumway-Cook and M. H. Woollacott, *Motor Control: Translating Research Into Clinical Practice*. Baltimore, MD, USA: Lippincott Williams & Wilkins, 2007.

[20] T. M. Herter, S. H. Scott, and S. P. Dukelow, "Vision does not always help stroke survivors compensate for impaired limb position sense," *J. Neuroeng. Rehabil.*, vol. 16, no. 1, p. 129, Dec. 2019.

[21] C. E. Winward, P. W. Halligan, and D. T. Wade, "Current practice and clinical relevance of somatosensory assessment after stroke," *Clin. Rehabil.*, vol. 13, no. 1, pp. 48–55, Jan. 1999.

[22] S. Schabrun and S. Hillier, "Evidence for the retraining of sensation after stroke: A systematic review," *Clin. Rehabil.*, vol. 23, no. 1, pp. 27–39, Jan. 2009.

[23] J. E. Sullivan and L. D. Hedman, "Sensory dysfunction following stroke: Incidence, significance, examination, and intervention," *Top Stroke Rehabil.*, vol. 15, no. 3, pp. 200–217, May/Jun. 2008.

[24] C. E. Winward, P. W. Halligan, and D. T. Wade, "The rivermead assessment of somatosensory performance (RASP): Standardization and reliability data," *Clin. Rehabil.*, vol. 16, no. 5, pp. 523–533, Aug. 2002.

[25] L. Carey and T. Matyas, "Frequency of discriminative sensory loss in the hand after stroke in a rehabilitation setting," *J. Rehabil. Med.*, vol. 43, no. 3, pp. 257–263, 2011.

[26] L. Connell, N. Lincoln, and K. Radford, "Somatosensory impairment after stroke: Frequency of different deficits and their recovery," *Clin. Rehabil.*, vol. 22, no. 8, pp. 758–767, Aug. 2008.

[27] R. L. Sacco, J. A. Bello, R. Traub, and J. C. Brust, "Selective proprioceptive loss from a thalamic lacunar stroke," *Stroke*, vol. 18, no. 6, pp. 1160–1163, Nov. 1987.

[28] J. A. Gutrecht, A. A. Zamani, and D. N. Pandya, "Lacunar thalamic stroke with pure cerebellar and proprioceptive deficits," *J. Neurol., Neurosurg. Psychiatry*, vol. 55, no. 9, pp. 854–856, Sep. 1992.

[29] J. S. Kim, "Pure sensory stroke. Clinical-radiological correlates of 21 cases," *Stroke*, vol. 23, no. 7, pp. 983–987, Jul. 1992.

[30] M. Y. Lee, S. H. Kim, B. Y. Choi, C. H. Chang, S. H. Ahn, and S. H. Jang, "Functional MRI finding by proprioceptive input in patients with thalamic hemorrhage," *NeuroRehabilitation*, vol. 30, no. 2, pp. 131–136, Mar. 2010.

[31] S. Shintani, S. Tsuruoka, and T. Shiigai, "Pure sensory stroke caused by a cerebral hemorrhage: Clinical-radiologic correlations in seven patients," *AJNR Amer. J. Neuroradiol.*, vol. 21, no. 3, pp. 515–520, 2000.

[32] C. Derouesné, J. L. Mas, F. Bolgert, and P. Castaigne, "Pure sensory stroke caused by a small cortical infarct in the middle cerebral artery territory," *Stroke*, vol. 15, no. 4, pp. 660–662, Jul. 1984.

[33] J. S. Kim, "Patterns of sensory abnormality in cortical stroke: Evidence for a dichotomized sensory system," *Neurology*, vol. 68, no. 3, pp. 174–180, Jan. 2007.

[34] S. E. Findlater *et al.*, "Lesion locations associated with persistent proprioceptive impairment in the upper limbs after stroke," *NeuroImage: Clin.*, vol. 20, pp. 955–971, Jan. 2018.

[35] S. P. Dukelow, T. M. Herter, S. D. Bagg, and S. H. Scott, "The independence of deficits in position sense and visually guided reaching following stroke," *J. Neuroeng. Rehabil.*, vol. 9, no. 1, p. 72, 2012.

[36] A. Kusoffsky, I. Wadell, and B. Y. Nilsson, "The relationship between sensory impairment and motor recovery in patients with hemiplegia," *Scand. J. Rehabil. Med.* , vol. 14, no. 1, pp. 27–32, 1982.

[37] W. de Weerdt, N. B. Lincoln, and M. A. Harrison, "Prediction of arm and hand function recovery in stroke patients," *Int. J. Rehabil. Res.*, vol. 10, pp. 110–112, Dec. 1987.

[38] I. U. Wadell, A. Kusoffsky, and B. Y. Nilsson, "A follow-up study of stroke patients 5–6 years after their brain infarct," *Int. J. Rehabil. Res.*, vol. 10, no. 4, pp. 103–110, 1987.

[39] D. L. Smith, A. J. Akhtar, and W. M. Garraway, "Proprioception and spatial neglect after stroke," *Age Ageing*, vol. 12, no. 1, pp. 63–69, 1983.

[40] C. Chester and C. McLaren, "Somatosensory evoked response and recovery from stroke," *Arch. Phys. Med. Rehabil.*, vol. 70, no. 7, pp. 520–525, 1989.

[41] G. N. Davidoff, O. Keren, H. Ring, and P. Solzi, "Acute stroke patients: Long-term effects of rehabilitation and maintenance of gains," *Arch. Phys. Med. Rehabil.*, vol. 72, no. 11, pp. 869–873, Oct. 1991.

[42] R. J. Prescott, W. M. Garraway, and A. J. Akhtar, "Predicting functional outcome following acute stroke using a standard clinical examination," *Stroke*, vol. 13, no. 5, pp. 641–647, Sep. 1982.

[43] B. D. Zeman and C. Yiannikas, "Functional prognosis in stroke: Use of somatosensory evoked potentials," *J. Neurol., Neurosurg. Psychiatry*, vol. 52, no. 2, pp. 242–247, Feb. 1989.

[44] L. U. Pumpa, L. S. Cahill, and L. M. Carey, "Somatosensory assessment and treatment after stroke: An evidence-practice gap," *Austral. Occupational Therapy J.*, vol. 62, no. 2, pp. 93–104, Apr. 2015.

[45] J. D. G. Watson, J. G. Colebatch, and D. I. McCloskey, "Effects of externally imposed elastic loads on the ability to estimate position and force," *Behavioural Brain Res.*, vol. 13, no. 3, pp. 267–271, Sep. 1984.

[46] J. F. Soechting, "Does position sense at the elbow reflect a sense of elbow joint angle or one of limb orientation?" *Brain Res.*, vol. 248, no. 2, pp. 392–395, Sep. 1982.

[47] J. R. Lackner and P. DiZio, "Human orientation and movement control in weightless and artificial gravity environments," *Exp. Brain Res.*, vol. 130, no. 1, pp. 2–26, Jan. 2000.

[48] G. E. Ansems, T. J. Allen, and U. Proske, "Position sense at the human forearm in the horizontal plane during loading and vibration of elbow muscles," *J. Physiol.*, vol. 576, no. 2, pp. 445–455, Oct. 2006.

[49] L. A. Jones, "Motor illusions: What do they reveal about proprioception?" *Psychol. Bull.*, vol. 103, no. 1, pp. 72–86, 1988.

[50] N. Lincoln, J. Crow, J. Jackson, G. Waters, S. Adams, and P. Hodgson, "The unreliability of sensory assessments," *Clin. Rehabil.*, vol. 5, no. 4, pp. 273–282, Nov. 1991.

[51] W. M. Garraway, A. J. Akhtar, S. M. Gore, R. J. Prescott, and R. G. Smith, "Observer variation in the clinical assessment of stroke," *Age Ageing*, vol. 5, no. 4, pp. 233–240, 1976.

[52] S. S. Kessner, U. Bingel, and G. Thomalla, "Somatosensory deficits after stroke: A scoping review," *Topics Stroke Rehabil.*, vol. 23, no. 2, pp. 136–146, Feb. 2016.

[53] N. Gurari, J. M. Drogos, and J. P. A. Dewald, "Individuals with chronic hemiparetic stroke can correctly match forearm positions within a single arm," *Clin. Neurophysiol.*, vol. 128, no. 1, pp. 18–30, Jan. 2017.

[54] F. Marini, S. Contu, C. W. Antuvan, P. Morasso, and L. Masia, "The influence of external forces on wrist proprioception," *Frontiers Hum. Neurosci.*, vol. 11, p. 440, Aug. 2017.

[55] D. Phillips and A. Karduna, "No relationship between joint position sense and force sense at the shoulder," *J. Motor Behav.*, vol. 50, no. 2, pp. 228–234, Mar. 2018.

[56] I. A. Kuling, E. Brenner, and J. B. J. Smeets, "Proprioception is robust under external forces," *PLoS ONE*, vol. 8, no. 9, Sep. 2013, Art. no. e74236.

[57] I. A. Kuling, E. Brenner, and J. B. J. Smeets, "Torques do not influence proprioceptive localization of the hand," *Exp. Brain Res.*, vol. 233, no. 1, pp. 61–68, Jan. 2015.

[58] P. J. Cordo and M. Flanders, "Sensory control of target acquisition," *Trends Neurosciences*, vol. 12, no. 3, pp. 110–117, Mar. 1989.

[59] W. G. Darling and J. M. Hondzinski, "Kinesthetic perceptions of earth- and body-fixed axes," *Exp. Brain Res.*, vol. 126, no. 3, pp. 417–430, May 1999.

[60] C. J. Worringham and G. E. Stelmach, "The contribution of gravitational torques to limb position sense," *Exp. Brain Res.*, vol. 61, no. 1, pp. 38–42, Dec. 1985.

[61] S. Marcora, "Perception of effort during exercise is independent of afferent feedback from skeletal muscles, heart, and lungs," *J. Appl. Physiol.*, vol. 106, no. 6, pp. 2060–2062, Jun. 2009.

[62] B. Pageaux, "Perception of effort in exercise science: Definition, measurement and perspectives," *Eur. J. Sport Sci.*, vol. 16, no. 8, pp. 885–894, Nov. 2016.

[63] L. D. Walsh, S. C. Gandevia, and J. L. Taylor, "Illusory movements of a phantom hand grade with the duration and magnitude of motor commands," *J. Physiol.*, vol. 588, no. 8, pp. 1269–1280, Apr. 2010.

[64] J. L. Smith, M. Crawford, U. Proske, J. L. Taylor, and S. C. Gandevia, "Signals of motor command bias joint position sense in the presence of feedback from proprioceptors," *J. Appl. Physiol.*, vol. 106, no. 3, pp. 950–958, Mar. 2009.

[65] A. Polit and E. Bizzi, "Processes controlling arm movements in monkeys," *Science*, vol. 201, no. 4362, pp. 1235–1237, Sep. 1978.

[66] P. R. Davidson and D. M. Wolpert, "Widespread access to predictive models in the motor system: A short review," *J. Neural Eng.*, vol. 2, no. 3, pp. S313–S319, Sep. 2005.

[67] R. C. Miall and D. M. Wolpert, "Forward models for physiological motor control," *Neural Netw.*, vol. 9, no. 8, pp. 1265–1279, Nov. 1996.

[68] P. M. Bays and D. M. Wolpert, "Computational principles of sensorimotor control that minimize uncertainty and variability," *J. Physiol.*, vol. 578, no. 2, pp. 387–396, Jan. 2007.

[69] D. M. Wolpert, Z. Ghahramani, and M. I. Jordan, "An internal model for sensorimotor integration," *Science*, vol. 269, no. 5232, pp. 1880–1882, 1995.

[70] J. A. Winter, T. J. Allen, and U. Proske, "Muscle spindle signals combine with the sense of effort to indicate limb position," *J. Physiol.*, vol. 568, no. 3, pp. 1035–1046, Nov. 2005.

[71] N. Bhushan and R. Shadmehr, "Computational nature of human adaptive control during learning of reaching movements in force fields," *Biol. Cybern.*, vol. 81, no. 1, pp. 39–60, Jul. 1999.

[72] D. M. Wolpert, S. J. Goodbody, and M. Husain, "Maintaining internal representations: The role of the human superior parietal lobe," *Nature Neurosci.*, vol. 1, no. 6, pp. 529–533, Oct. 1998.

[73] T. J. Allen and U. Proske, "Effect of muscle fatigue on the sense of limb position and movement," *Exp. Brain Res.*, vol. 170, no. 1, pp. 30–38, Mar. 2006.

[74] D. J. Goble and S. H. Brown, "Upper limb asymmetries in the matching of proprioceptive versus visual targets," *J. Neurophysiol.*, vol. 99, no. 6, pp. 3063–3074, 2008.

[75] P. Cordo, L. Carlton, L. Bevan, M. Carlton, and G. K. Kerr, "Proprioceptive coordination of movement sequences: Role of velocity and position information," *J. Neurophysiol.*, vol. 71, no. 5, pp. 1848–1861, May 1994.

[76] R. A. R. C. Gopura, D. S. V. Bandara, K. Kiguchi, and G. K. I. Mann, "Developments in hardware systems of active upper-limb exoskeleton robots: A review," *Robot. Auton. Syst.*, vol. 75, pp. 203–220, Jan. 2016.

[77] D. J. Goble, "Proprioceptive acuity assessment via joint position matching: From basic science to general practice," *Phys. Therapy*, vol. 90, no. 8, pp. 1176–1184, Aug. 2010.

[78] D. J. Goble, E. A. Hurvitz, and S. H. Brown, "Deficits in the ability to use proprioceptive feedback in children with hemiplegic cerebral palsy," *Int. J. Rehabil. Res.*, vol. 32, no. 3, pp. 267–269, 2009.

[79] D. J. Goble, B. C. Noble, and S. H. Brown, "Proprioceptive target matching asymmetries in left-handed individuals," *Exp. Brain Res.*, vol. 197, no. 4, pp. 403–408, Aug. 2009.

[80] D. J. Goble and S. H. Brown, "Task-dependent asymmetries in the utilization of proprioceptive feedback for goal-directed movement," *Exp. Brain Res.*, vol. 180, no. 4, pp. 693–704, Jun. 2007.

[81] D. J. Goble, C. A. Lewis, E. A. Hurvitz, and S. H. Brown, "Development of upper limb proprioceptive accuracy in children and adolescents," *Hum. Movement Sci.*, vol. 24, no. 2, pp. 155–170, Apr. 2005.

[82] D. E. Adamo, B. J. Martin, and S. H. Brown, "Age-related differences in upper limb proprioceptive acuity," *Perceptual Motor Skills*, vol. 104, no. 3, pp. 1297–1309, Jun. 2007.

[83] L. D. Walsh, C. W. Hesse, D. L. Morgan, and U. Proske, "Human forearm position sense after fatigue of elbow flexor muscles," *J. Physiol.*, vol. 558, no. 2, pp. 705–715, Jul. 2004.

[84] C. Brockett, N. Warren, J. E. Gregory, D. L. Morgan, and U. Proske, "A comparison of the effects of concentric versus eccentric exercise on force and position sense at the human elbow joint," *Brain Res.*, vol. 771, no. 2, pp. 251–258, Oct. 1997.

[85] A. Tsay, T. J. Allen, and U. Proske, "Position sense at the human forearm after conditioning elbow muscles with isometric contractions," *Exp. Brain Res.*, vol. 233, no. 9, pp. 2635–2643, Sep. 2015.

[86] A. J. Tsay, M. J. Giummarra, T. J. Allen, and U. Proske, "The sensory origins of human position sense," *J. Physiol.*, vol. 594, no. 4, pp. 1037–1049, Feb. 2016.

[87] D. A. Winter, *Biomechanics and Motor Control of Human Movement*. Hoboken, NJ, USA: Wiley, 2009.

[88] R. Van Noorden, B. Maher, and R. Nuzzo, "The top 100 papers," *Nature*, vol. 514, p. 550, Oct. 2014.

[89] D. G. Altman and J. M. Bland, "Measurement in medicine: The analysis of method comparison studies," *J. Roy. Statist. Soc. D, Statistician*, vol. 32, no. 3, pp. 307–317, Sep. 1983.

[90] J. M. Bland and D. G. Altman, "Statistical methods for assessing agreement between two methods of clinical measurement," *Lancet*, vol. 327, no. 8476, pp. 307–310, Feb. 1986.

[91] J. M. Bland and D. G. Altman, "Comparing methods of measurement: Why plotting difference against standard method is misleading," *Lancet*, vol. 346, no. 8982, pp. 1085–1087, Oct. 1995.

[92] J. M. Bland and D. G. Altman, "Measuring agreement in method comparison studies," *Stat. Methods Med. Res.*, vol. 8, no. 2, pp. 135–160, Jun. 1999.

[93] J. M. Bland and D. G. Altman, "Applying the right statistics: Analyses of measurement studies," *Ultrasound Obstetrics Gynecol.*, vol. 22, no. 1, pp. 85–93, Jul. 2003.

[94] J. W. Bartlett and C. Frost, "Reliability, repeatability and reproducibility: Analysis of measurement errors in continuous variables," *Ultrasound Obstetrics Gynecol.*, vol. 31, pp. 466–475, Feb. 2008.

[95] D. G. Altman, *Practical Statistics for Medical Research*. Boca Raton, FL, USA: CRC Press, 1990.

[96] M. Spitzer, J. Wildenhain, J. Rappsilber, and M. Tyers, "BoxPlotR: A web tool for generation of box plots," *Nature Methods*, vol. 11, no. 2, pp. 121–122, Feb. 2014.

[97] Q. Mourcou *et al.*, "Mobile phone-based joint angle measurement for functional assessment and rehabilitation of proprioception," *Biomed Res. Int.*, vol. 2015, p. 15, 2015, Art. no. 328142.

[98] L. M. Carey, T. A. Matyas, and L. E. Oke, "Sensory loss in stroke patients: Effective training of tactile and proprioceptive discrimination," *Arch. Phys. Med. Rehabil.*, vol. 74, no. 6, pp. 602–611, Jun. 1993.

[99] L. M. Carey, L. E. Oke, and T. A. Matyas, "Impaired touch discrimination after stroke: A quantiative test," *Neurorehabilitation Neural Repair*, vol. 11, no. 4, pp. 219–232, Jan. 1997.

[100] D. E. Adamo, N. B. Alexander, and S. H. Brown, "The influence of age and physical activity on upper limb proprioceptive ability," *J. Aging Phys. Activity*, vol. 17, no. 3, pp. 272–293, Jul. 2009.

[101] I. Cusmano *et al.*, "Evaluation of upper limb sense of position in healthy individuals and patients after stroke," *J. Healthcare Eng.*, vol. 5, no. 2, pp. 145–162, Jun. 2014.