Robot-Aided Assessment of Human Ankle Joint Position Sense and Motion Sense

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Abstract

Background -Numerous neurological and orthopedic conditions impair ankle proprioception resulting in gait and balance deficits. However, current clinical practice lacks accurate and reliable methods to assess proprioceptive function. To address this gap, we developed a robotic assessment system that provides accurate, objective, and reliable measures of human ankle position and motion sense acuitythat reflectproprioceptive function at this joint.

Methods -Ankle position sense and motion sense acuity were assessed in twenty healthy adult participantsemploying a psychophysical two-alternative forced-choice paradigm.An ankle robot deliveredtightly controlled passive, open kinematic ankle dorsiflexion/plantarflexion positions or velocities. The robot passively rotated aparticipant's ankle to two distinctplantarflexed positions for position sense testing, orthe ankle was plantarflexed at two distinct velocities for motion sense testing. After experiencing the two stimuli, participants verbally indicated which ankle position was more plantarflexedor which motionwas perceived as faster. Based on a participant's verbal responses, a psychometric function was fitted and the respective discrimination thresholds and intervals of uncertainty were derived. Additionally, test-retest reliability of the threshold measures was determined across three different experimental sessions for a subset of five participants.

Results -Analysis yielded a mean position discrimination threshold of 0.80° (SD: ± 0.10°), and a mean motion discrimination threshold of 0.73°/s (SD: ± 0.11°/s). Test-retest reliability of the threshold measures based on the intraclass correlation coefficient (ICC) was moderate to excellent in position sense (range, ICC = 0.86 [0.50 - 0.98]) and motion sense (range, ICC = 0.86 [0.57 - 0.99]) testing.

Conclusion -The results demonstrated the utility and reliability ofa robot-aided assessment of human ankle proprioceptive function paving the way to employ such systemsfor the fast and accurate diagnosisof proprioceptive dysfunction in clinical populations.

Background

Proprioception refers to the sense of limb position and motion[1]. The different submodalities of proprioception are passive or active joint position sense and joint motion sense. Proprioceptive afferents from the ankle joint are essential for the neural control of balance and postural stability [2, 3]. Numerous neurological disorders such as stroke [4], Parkinson's disease [5], and cerebral palsy [6] are associated with impaired ankle proprioception leading to slower gait, increased postural sway, and poor balance [7]. Because movement and the perception of movement are necessarily linked, it is difficult to separate the effects of impaired somatosensation from deficits in multisensory or sensorimotor integration or dysfunction of motor control processes. Indirect outcome measures to reflect ankle proprioception that were previously reported include various balance measures such as the center of pressure (COP) derived variables (e.g., COP displacement or velocity) [8-12], reaction force [13], or biomechanical measures such as joint kinematics or kinetics [14], and electromyographic activity [15]. Moreover, the clinical rating scales (e.g., modified Nottingham Sensory Assessment) are coarse and not sensitive enough to detect or differentiate between subtle deficits of ankle movement [16, 17]. Direct, objective, sensitive, and reliable measures of ankle proprioception based on sensory psychophysics are available, but these have not been adapted in clinical practice.

Several methods have been applied to assess the submodalities of proprioception. Force or joint position matching approaches obtain a force reproduction or joint position sense error (JPSE) computed as the mean difference between a target and a matching position or force [18, 19]. Motion sense error has been typically reported as an error in judging movement direction or as the percentage of incorrect judgments between actual and perceived movement direction atdifferent velocities [20].

In addition, there are psychophysical procedures to assess proprioceptive function that yield detection and discrimination thresholds. A detection threshold, the minimum perceivable change in position or motion, serves as a measure of proprioceptive sensitivity. A position sense detection threshold is measured by presenting different positions at a constant velocity [18, 21], whereas a motion sense detection threshold is measured by presenting passive movements at different velocities [20, 22].A discrimination or just-noticeable-difference (JND) threshold is the smallest perceived difference between two positions or motions [23]. Obtaining proprioceptive discrimination threshold requires the accurate presentation of pairs of distinct joint positions ormotions [24]. Measures of proprioceptive acuity consist of two components –*bias* represents the systematic error, and *precision* indicates the random error [25]. Bias in proprioceptive acuity is usually evaluated in terms of a JND position or motion sense threshold. Precision reflects the agreement across all trials indicated by the interval of uncertainty of the psychometric function [23]. The smaller the interval of uncertainty, the higher precision of proprioceptive acuity.

Several experimental and robotic devices have been developed to evaluate ankle sensorimotor function in the past. The Active Movement Extent Discrimination Apparatus assessed ankle proprioception in weight-bearing/standing position[26, 27]. This evaluation yields a measure of proprioceptive function that is based on the integration of signals from multiple senses such as vision, the vestibular system, and proprioceptive signals from peripheral mechanoreceptors[28]. Other approaches applied an active ankle joint position reproduction test in a non-weight bearing condition without vision [26] using isokinetic dynamometers to measure the joint angular difference between the target and the active matching positions. Obtaining aJPSE during active movement reflects the performance of both proprioceptive and motor control processes. Therefore, to accurately quantify ankle proprioception, it is imperative to employ assessments that use non-weight-bearing passive movement tasks in the absence of vision to achieve the isolation of proprioceptive processing from other neural processes involved in motor control.

Previous researchshowed that psychophysical threshold methods to obtain joint position sense discrimination threshold in the passive movement are more precise than an active joint position reproduction test [23, 24]. For this type of testing, robotic devices are good choices as they deliver tightlycontrolled passive movements. The robot-aided discrimination assessment for wrist position sense acuity has been studied [23, 24]. However, to our knowledge, there are no reports that used of robots to evaluate psychophysical ankle position and motion sense discrimination thresholds. We here present the design of a simple, one-degree-of-freedom (DOF)ankle robot that can passively rotate the human ankle joint around its medial-lateral axis resulting dorsiflexion/plantarflexion (DFPF)to obtain psychophysical measures of “pure” ankle proprioceptive acuity by generating ankle position and motion discrimination thresholds.

Methods

Participants

Twenty healthy young adults (Mean Age = 24.9 ± 4.1 yrs.; 14 males) with no reported history of a musculoskeletal, neurological, or orthopedic impairment that could have affected lower limb movement control were recruited for study participation. The experiment protocol was conducted with the approval of the Human Participants Ethics Committee (20200134) ofSouthern University of Science and Technology, China. All participants were informed about the experiment and voluntarily consented to participate in the study. All participants in this study were right footed as determined by a footedness questionnaire [29].

Robotic ankle device

We designed a robotic device to deliver passive rotation of the ankle jointarounditsmedial-lateral joint axis. The assembly of the robotic ankle is depicted in**Fig. 1A**. The actuator is composed of a DC motor (305013, Maxon, 200 W) with a gearbox (326664, Maxon, gear ratio: 51:1)and a built-in 14-bit optical encoder (575827, Maxon). The robotic ankle was programmed to generate precise speeds and trajectories with well-tuned internal PID gains to move the ankle passively. The maximum torque provided by the actuator is 12 Nm. Repetitive positioning accuracy is the ability of the robotic device to arrive at the prescribed position repeatedly. To determine the sensitivity of ankle robot, we evaluated the tracking accuracy of the robotic ankle by the error between the actual trajectory and the reference trajectory (a sinusoidal signal with amplitude at 15 degrees and a period of 12 seconds), which is shown in **Fig. 1B**. During repetitive passive movements, the robotic ankle ensured a highly precise repetitive positioning accuracy with a mean error of 0.04° (range: 0 - 0.11°) to reach the largest target position (± 15°) in our experiment protocols. As shown in **Fig. 1B**,the dynamic tracking accuracy of the actuator was always below 0.2° during the sinusoidal tracking task. Foot straps stabilize the testing foot on a carbon fiber foot pedal (L: 33 cm; W: 13 cm).A carbon fiber shaft rod (maximum H: 12 cm) was attached to the actuator’s output shaft to adjust the ankle to align with the motor axis.The use of carbon fiber components provides high durability while achieving a lower mass of the device, which reduces the necessary torque output during ankle rotation. A heel blocker screwed in the foot pedal allows for an adjustable forward/backward foot length in the range of 6 cm. Calibrated scales were included in the foot pedal to guarantee accurate foot positions for various foot sizes. As shown in **Fig. 1B**, the electronic control apparatus was mounted on a mobile platform with lockable K-92-50F type wheels.The test protocol software uses MATLAB codeand to determines the order and size of the next position or motion stimuli for each trial. It communicates with a customized control software routine developed in LabVIEW to control the output of the DC motor.

Procedure

Participants were seated in a chair with their dominant feet on the foot pedal. The test setup is shown in **Fig. 1B**. The participants were blindfolded and received static pink noise via headphones to block any visual and/or auditory cues during the assessment. At the beginning of testing, height and distance of the lateral malleolus from the heel were obtained (see **Fig. 1A**). This anthropometric information was used to align the axis of rotation of the ankle joint with the rotation axis of the actuator. We then adjusted the leg fixation cushion to support the leg at 45° relative to the horizontal to maintain the ankle at a neutral (90°) joint position (see **Fig. 1B**). The robotic device measured both passive and active range of motion at the ankle joint in the DFPF axis. Two types of tests were conducted to obtain measures of ankle position sense or motion sense acuity. The order of the assessments (motion vs. position sense testing) was pseudo-randomized between participants to control for order effects. Each type of assessment consisted of 30 trials. Breaks were allowed after 15 trials or when the participant needed a rest. Total duration of testing for both assessments was approximately 30 minutes.To assure fast convergence towards the true psychophysical threshold, an adaptive Bayesian algorithm,the *psi-marginal* method [30]was employed to select the next comparison stimulus based on the previous responses of the participant.

Assessment of position sense acuity

The robot rotated the foot at a constant velocity of 2°/s to two distinctankle positions in each trial: at 15° plantarflexion from the joint neutral position represented the*reference* position and a *comparison* position of variable amplitude that ranged between 14.5 - 13.9°across trials (see **Fig. 2**). The low joint velocity allowed the participant sufficient time to focus on the final displacement which was held for 2 seconds[23]. The reference and comparison stimuli were presented in random order between trials. Within each trial, the two stimuli were separated by a two-second interval. At the end of each trial, participants verbally indicated which joint position they perceived as more plantarflexed (first or second).The experimenter then entered the participant's binary response into the testing software, and the adaptive algorithm then determined the size of next comparison stimulus within a biomechanically possible stimulus range [31].

Assessment of motion sense acuity

From the neutral joint position,the robot rotated a participant's ankle towards plantarflexion at two different velocities - a *reference* speed (5°/s) and a *comparison* speed ranging between 4.5 - 3.9°/s (see

Fig. 2). The movement amplitude was fixed to 5°. All other aspects of the procedure were identical to the procedure for joint position sense testing.At the end of each trial, participants verbally indicated which of the two movements was perceived as faster (first or second).

Ankle joint discrimination thresholds

After 30 trials, the stimulus difference size and the correct response rate data were fitted for each participant to yield a psychometric function [24]. Based on the fitted function, the stimulus difference size corresponding to the 75% correct response rate served as the discrimination or just-noticeable difference (JND) threshold as a measure of bias [23]. The interval of uncertainty (IU), which is the range of the stimulus difference size between 60% and 90% probability of correct response,represents a measure of perceptual precision (see **Fig. 3**).

For this test, a JND position sense threshold represents the smallest difference in ankle plantarflexion position required to discriminate a *comparison* position from the *reference* position of 15° ankle plantarflexion. The JND motion sense threshold represents the minimum difference in velocity required to discriminate a *comparison* from the *reference*velocity of 5°/s.

Reliability

To assess the test-retest reliability of the threshold estimates across time, we repeated the procedure for two additional days (Day2 and Day3) in a subset of five subjects. They participated in the testing on three different days during three visits at the same time of the day, which were spaced exactly a weekapart. The ankle height and foot length adjustments were made based on participant's anthropometrics, and were kept consistent in all the three testing sessions.The intraclass correlation coefficient (ICC) estimates along with their 95% confidence intervals were calculated using R version 4.1.2 based on a single-rating (k=1), two-way mixed-effects model for absolute agreement. An ICC greater than 0.90 was considered excellent, between 0.75 and 0.90 was good, between 0.50 and 0.75 was moderate, and less than 0.50 was poor [32].

Results

The normality of the variables was evaluated using Shapiro-Wilk tests. Except for motion sense IU, all outcome measures (JND position sense threshold, JND motion sense threshold, and position sense IU) were normally distributed. Exemplar verbal response data from a single participant during the position and the motion sense acuity tests are shown in **Fig. 4**.

Across all participants, the mean JND position sense threshold was computed as 0.80° ± 0.10° (range: 0.64 - 0.97°). The corresponding mean position sense IU, or random error, was computed as 0.84° ± 0.41° (range: 0.13° - 1.66°). Mean JND motion sense threshold was 0.73°/s ± 0.11°/s (range: 0.55°/s - 0.94°/s) and mean motion sense IU was calculated to be 0.60°/s ± 0.29°/s (range: 0.23°/s - 1.08°/s; see the box and whisker plots in **Fig. 5**.

In order to determine the relationship between position sense and motion sense acuity, correlation analyses with all outcome measures were conducted. No significant correlation was found between the measures of position and motion sense bias (JND threshold: $r = 0.15$, $p = 0.53$) and precision (IU: $r = 0.05$, $p = 0.84$) [33].

To determine the reliability of the assessments, we tested a subset of five participants on three different days (Day1, Day2, and Day3; see **Fig. 6**). The results indicated that the JND position sense threshold had a moderate to excellent reliability (ICCs: 0.50 - 0.98) with an average ICC = 0.86. JND motion sense testing showed moderate to excellent reliability (ICCs: 0.57 - 0.99) with an average ICC = 0.88. Furthermore, the standard error of measurement (SEM) for the JND position sense threshold was 0.0173°, and 0.0197°/s for the JND motion sense threshold.

Discussion

The current studyintroduced a newly designed single DOF robotic system for the assessment of human ankle position and motion sense. The main outcomes of the study were: First, the robot-aided assessment yielded objective measures of bias and precision for two modalities of ankle joint proprioception - joint position sense and motion sense in a sample of healthy human adult participants. Second, we established the test-retest reliability of the device over repeated testing. The data document that our robot-aided approach of producing open kinematic, non-weight bearing, and passive rotation of the ankle coupled with a psychophysical assessment procedure provides valid and reliable estimates of ankle proprioceptive acuity.

Sensitivity of the device

We established the sensitivity of ankle robot, i.e., whether the system was capable of delivering precise passive dorsiflexion/plantarflexion movements, by evaluating the tracking accuracy of the robotic ankle. These results (see **Fig. 1B**) showed the sensitivity of the developed robotic ankle and the PID controller implemented to precisely generate the desired trajectory for position and motion sense test protocols. With the robot’s actuator resolution at 0.00043° and the robot’s absolute mean positioning error at 0.04° during repeated passive movements, as well as the repeated measurement error at 0.0173° and 0.0197°/s for position and motion sense testing, the obtained mean JND position sense threshold of 0.80° observed in our participants is above the measurement error by more than an order of magnitude. This implies that the device allows more than enough sensitivity for the assessment of ankle proprioception.

One caveat concerns the assumption that the human ankle has a fixed center of rotation during dorsiflexion/plantarflexion that is perfectly aligned with the motor’s axis of rotation. To ensure consistency in testing and to reduce possible misalignment between the human ankle joint axis and the motor's axis as best as possible, the height and the length of the foot pedal were adjusted to align both axes at the beginning of each experimental session. Our high inter-test reliability observed during repeated testing sessions suggests that the influence of human-robot axis misalignment on the obtained measures of ankle proprioceptive function is negligible.

Comparing our approach to different methods of measuring ankle proprioception

This new robotic device for the assessment of ankle proprioceptive function deviates from previous designs in several aspects: First, it attempts to obtain a measure of "pure" proprioception that removes the influence of other, non-proprioceptive sensory signals. Second, it removes any contribution or interference from motor signals as the robot passively rotates the ankle. This is important with respect to clinical populations that may have compromised motor function. In such cases, it becomes difficult to determine to what extent an elevated threshold measurement reflects impaired motor or proprioceptive dysfunction. In contrast, there are approaches where the user/patient assumes a weight-bearing, standing position with eyes open and judges the ankle/foot position while the foot rests on a tilted platform [26]. The resulting perceptual measures of ankle position have been shown to be sensitive to identify age-related differences [34], but they reflect at best an indirect measure of ankle proprioception because the influence of other sensory modalities, as well as the contribution of other neural processes such as multimodal sensory integration, sensorimotor integration, voluntary motor execution and involuntary postural reflex activity affecting on a perceptual judgment are not controlled [28]. Such a whole-body approach does reflect on the function of the complete sensorimotor system in judging joint positions. However, its clinical usefulness is limited as it does not allow the differentiation between a proprioceptive or motor deficit, as well the effect of compensatory mechanisms that are common in orthopedic or neurological diseases that are known to affect balance and posture [35, 36]. These compensatory mechanisms have been documented to rely on other sensory modalities such as vision [37], vestibular [38], and haptic function [39].

A related approach by Deshpande and colleagues evaluates ankle proprioception in a weight-bearing, standing position [40] while the ankle is passively rotated. Processes of visuo-proprioceptive integration are removed by asking the participants to close their eyes. The resulting measure of ankle proprioception represents the minimum time to detect passive movement at a constant velocity of 0.25°/s reflecting on the sensitivity of the passive joint motion sense.

Several studies employed commercially available isokinetic devices to measure ankle position sense acuity of the non-weight-bearing ankle during an active joint position reproduction task [41, 42]. The resulting joint position sense error was approximately 7-9% of the target ankle angle [43]. A study on ankle plantarflexion with a reference position of 25° reported an average active JPSE of 1.96°, which represents a relative acuity of ~ 8% with respect to the reference [44]. Yet, another study using active motion yielded high JPSE values of about 60% of the target angle [45], indicating that, depending on the active motion setup, JPSE values can be highly variable.

A recent study using the manually operated ankle proprioceptive assessment system (APAS) developed by our group examined ankle proprioceptive function in young adults and yielded an average ankle JND threshold of 2.4° or 16% of the reference angle of 15° [46].

In the current study, the robotic device obtained proprioceptive discrimination thresholds for flexion DOF of the ankle joint. The mean ankle position sense threshold of 0.80° corresponded to 5.3% relative to the reference position of 15°. This is a slightly smaller value than those reported by the above-mentioned studies that assessed active position sense [43], which is not unexpected as thresholds obtained under passive motion conditions tend to be lower than those under comparable active motion conditions [23]. Moreover, differences between robotic and manual delivery of passive movements during proprioceptive assessments have been previously reported [47, 48]. In summary, given the available data on ankle proprioceptive acuity of human adults, the outcomes from our robotic ankle proprioceptive assessment system (RAPAS) are consistent with previous findings.

Comparing proprioceptive acuity across joints in healthy adults

The psychophysical discrimination thresholds method has been widely used to obtain estimates of proprioceptive acuity in the upper limb. In healthy adults, Elangovan et al. (2014) reported elbow joint position sense thresholds of 1.05° for a 10° reference position (relative bias ~10.5%) [23]. The same psychophysical approach applied to measure wrist joint position sense thresholds using a wrist robotic device yielded a mean wrist flexion threshold of 1.37° in healthy adults, which was about 9% relative to the reference displacement of 15° [49]. The data of the current study document that the position sense acuity of the ankle joint is in the approximate range of the wrist and elbow joints (i.e., 0.80° for a reference position of 15°).

In contrast to many of the above-described systems, this robotic device can assess ankle position as well as motion sense. A mean JND motion sense threshold of 0.73°/s, approximately 14.6% of the reference velocity 5°/s was observed in our sample of young healthy adults. It is noteworthy that no close relationship was observed between measures of ankle position and motion sense acuity. That is to say, those with high position sense acuity do not necessarily have high motion sense acuity and vice versa. This shows the importance of measuring both position and motion sense for complete insight into ankle proprioception and its deficits in clinical populations. While we lack comparable data on ankle motion sense acuity, our JND position sense threshold results at the ankle are in a reasonable and comparable range of proprioceptive acuity reported in other joints [23, 47, 49].

Clinical implications and limitations

Very few studies have quantitatively examined lower extremity proprioception in clinical populations, especially the ankle joint. Most commonly, clinical practice and clinical reports used the clinical rating scales [16, 50], balance measures [8-13], or other biomechanical variables [14, 15] to determine ankle proprioceptive status. Robotic technology has been developed to diagnose proprioceptive dysfunction of the upper limb. For example, recent studies using a wrist/hand exoskeleton robotic system have documented its usefulness in the evaluation of the joint position sense in healthy individuals and stroke survivors [51-54]. The current study extended such application to the ankle joint, which is a critical joint for balance and locomotion. We designed a new robotic device and coupled it with an accurate and reliable psychophysical discrimination threshold testing method for the quantification of “pure” ankle proprioception. Importantly, it obtains measures of both proprioceptive bias and precision to comprehensively assess proprioceptive function or dysfunction in a clinical setting or for clinical research [55, 56].

The method does have limitations. It only provides information of proprioceptive status of a single joint, albeit this joint is known to be critical for balance function. In addition, it restricts the information from other sensory systems that could help to overcome possible proprioceptive deficits. Thus, one could argue it is not sensitive to possible compensatory mechanisms consciously or unconsciously employed by a person with compromised proprioception. While this is a valid argument, we would contend that the method is intentionally designed to obtain information of a person’s proprioceptive status in the absence of other mitigating factors to arrive at a measure that reflects proprioceptive processing and not additional neural processes such as multimodal sensory integration or sensorimotor integration.

Conclusion

We here present a roboticsystem for the fast and objective assessment of ankle proprioceptive function. The robotic technology allows for the precise delivery of passive movement at the ankle joint. Coupled with an adaptive psychophysical testing paradigm, it is capable ofreliably and comprehensively assessing two major modalities of proprioceptive function - ankle position and motion sense. It yields established psychophysical measures of proprioceptive bias and precision, which are known to be affected in clinical populations with compromised proprioception, such as survivors of stroke [54] or children with developmental coordination disorder [55]. The system is easy to use and does not require extensive training, making it feasible to use as a diagnostic tool in clinical settings.

Abbreviations

SD, standard deviation

ICC, intraclass correlation coefficient

COP, center of pressure

JPSE, joint position sense error

JND, just-noticeable-difference

DOF, degree-of-freedom

DFPF, dorsiflexion/plantarflexion

IU, interval of uncertainty

SEM, standard error of measurement

RAPAS, robotic ankle proprioceptive assessment system

Declarations

Ethics approval and consent to participate:

The experiment protocol was conducted with the approval of the Human Participants Ethics Committee (20200134) of Southern University of Science and Technology, China. All participants were informed about the experiment and voluntarily consented to participate in the study.

Consent for publication:

not applicable

Availability of data and materials:

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests:

The authors declare that they have no competing interests

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Authors' contributions

Data collection and processing: QH; Figures and statistical analysis: QH, BZ; Manuscript writing and editing: QH, BZ, NE, MZ, JK.

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Figures

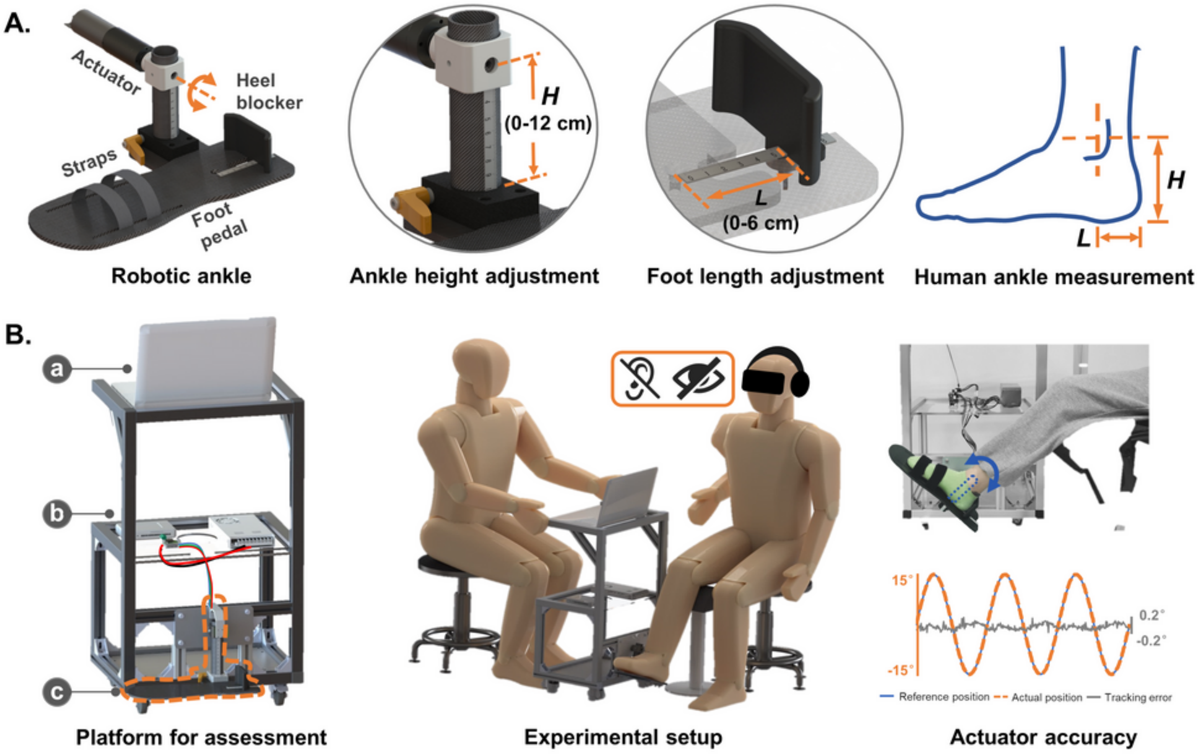

Figure 1

A. Robotic ankle proprioception system. The system includes an actuator (motor, gearbox, and encoder), the foot pedal with foot straps to secure forefoot position. The maximum range of ankle height (carbon fiber shaft rod) and foot length (heel blocker) is adjustable to human anthropometrics. The position of the lateral malleolus was determined (H: height; L: length from the heel) to align the motor axis with the human ankle joint axis. **B**. Overview of the complete system consisting of a) the computer to control the robot, b) the actuation system, and c) the robotic ankle. The participant was blindfolded to block vision and received auditory background noise via headphones to mask auditory cues. The experimenter adjusted the leg's height and angle fixing cushion to support the leg and relax the foot on the foot pedal.

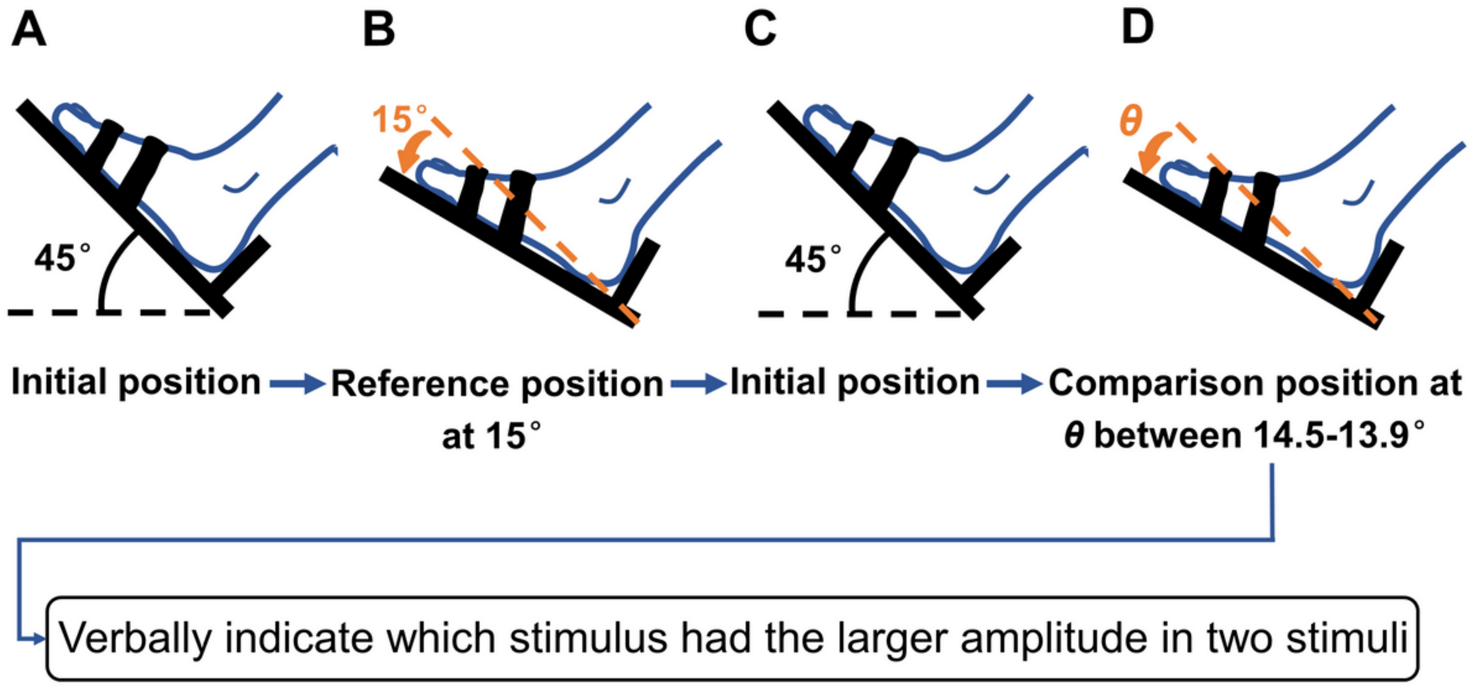

Figure 2

Example of showing a single trial during joint position sense discrimination assessment. **A**. The initial position of the foot pedal is 45° from the horizontal corresponding to a neutral 90° shank-foot angle. **B**. The robot rotates the foot to the reference position at 15° plantarflexion, and **C**. returns to the initial position. **D**. Subsequently, the robot rotates the foot to the comparison position (< 15° plantarflexion). Then, the participant verbally indicated which position was further from the initial position. During testing, the order of the reference and comparison positions (first or second) between trials is randomized.

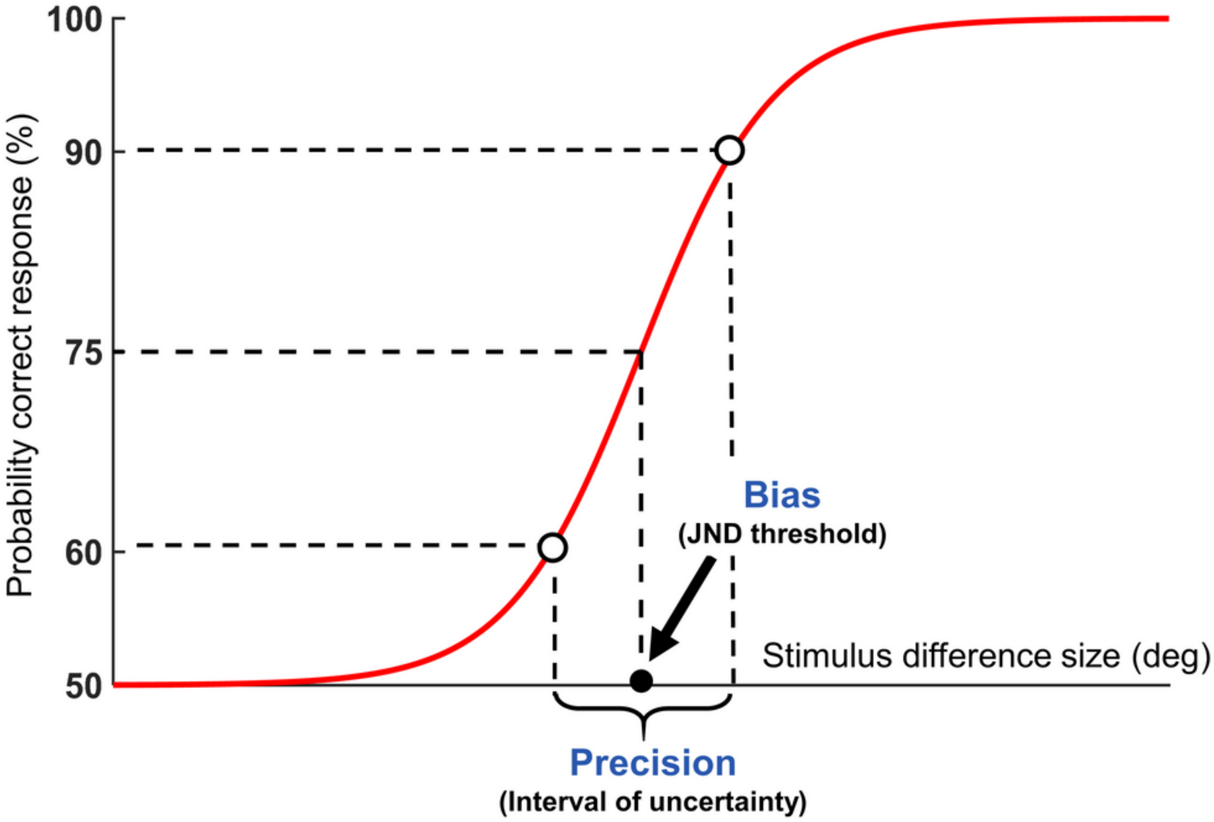

Figure 3

An exemplar psychometric function of a single participant. The stimulus size difference corresponding to the 75% correct response rate represents the just-noticeable difference (JND) threshold as a measure of bias. The interval of uncertainty (IU)between the 60-90thpercentile of the correct response rate represents a measure of precision here indicated by the curly bracket.

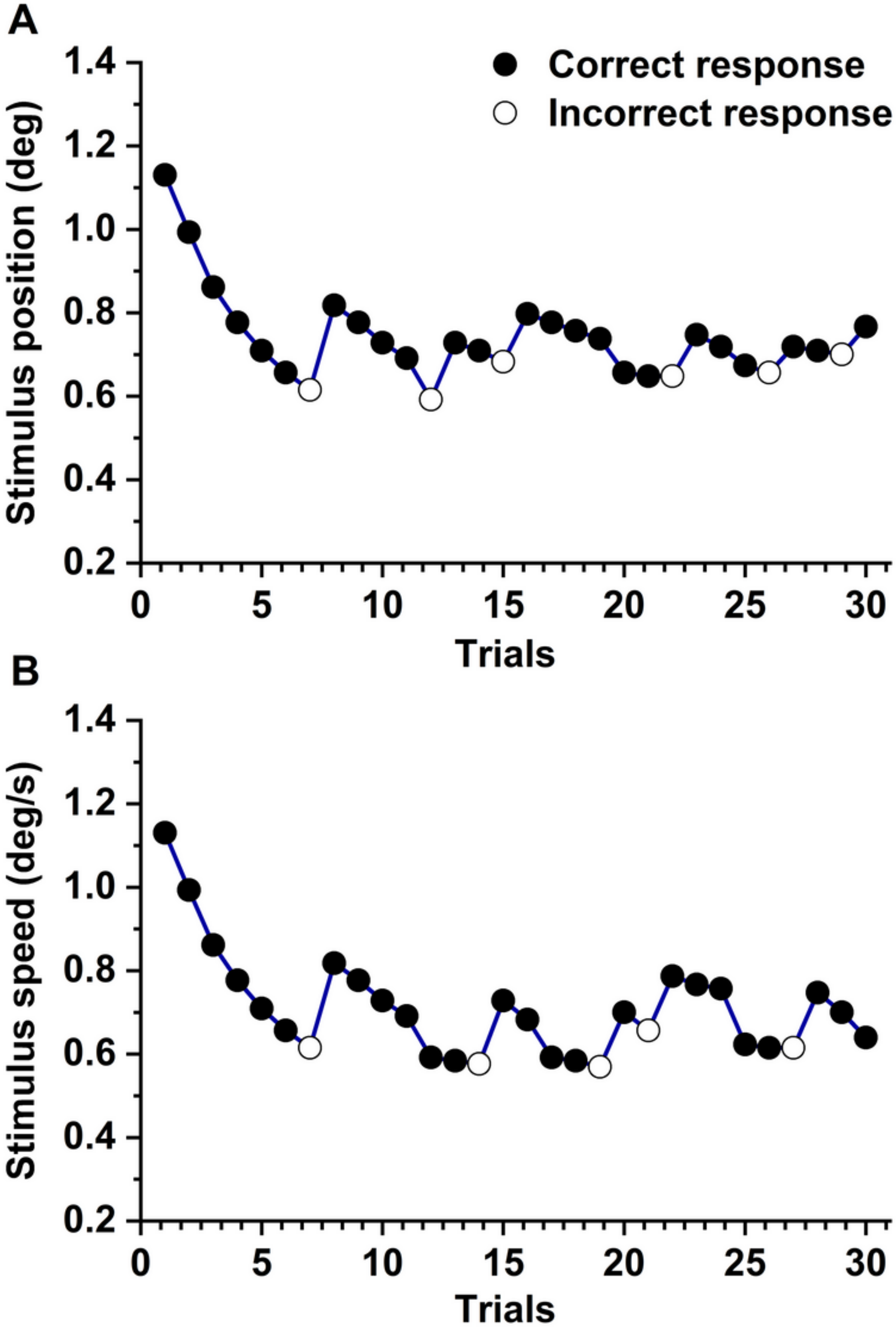

Figure 4

The exemplar dataset of both **A**. the position and **B**. the motion sense acuity assessments for one participant.

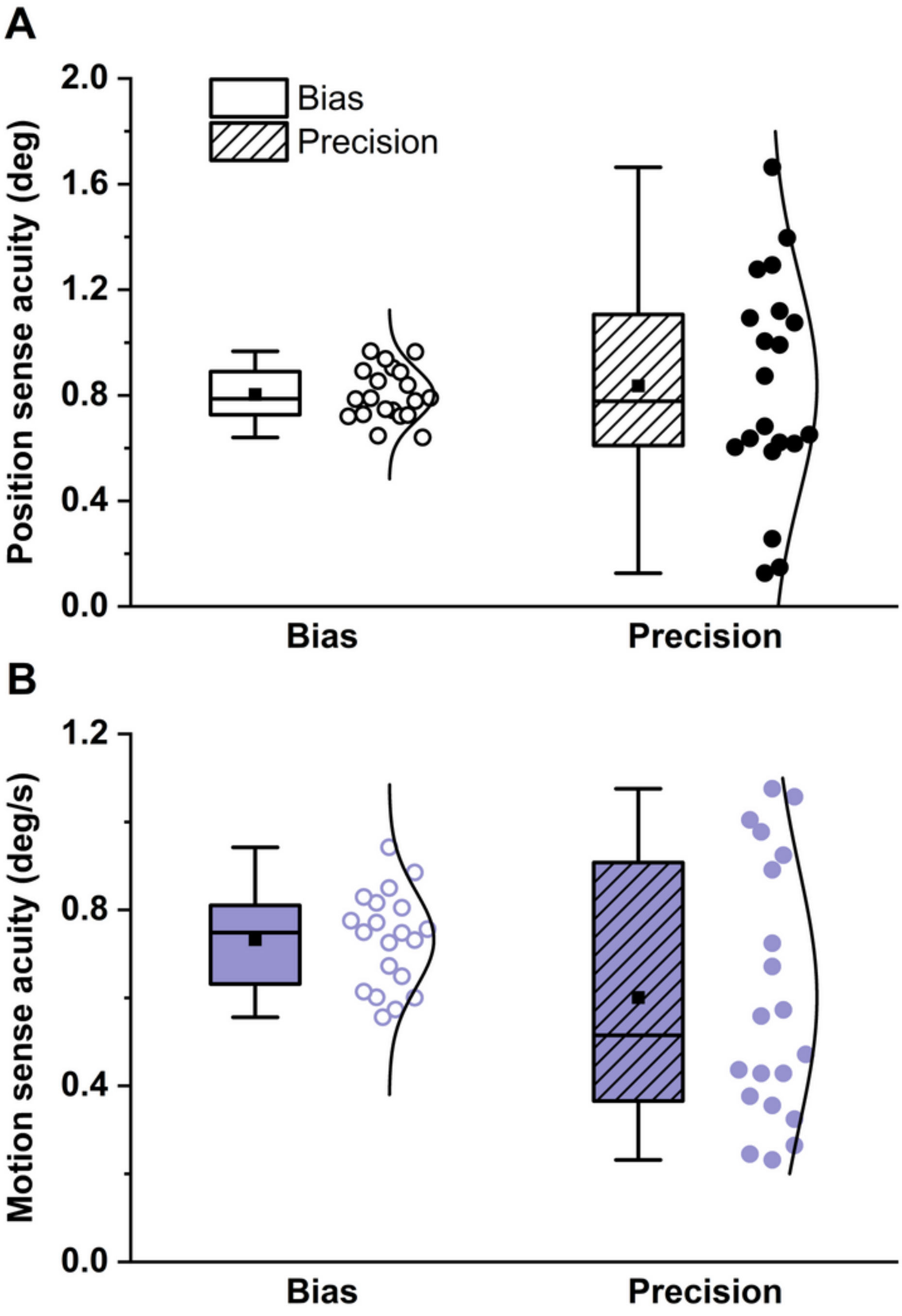

Figure 5

Position and motion sense bias and precision. Each box represents the 25-75th percentile. The middle line within a box represents the median. The solid square represents the mean and the whiskers represent the 1st and 99th percentile. **A**. position sense and **B.** motion sense acuity in all participants. Adjacent circles show all individual subject data and the corresponding distribution.

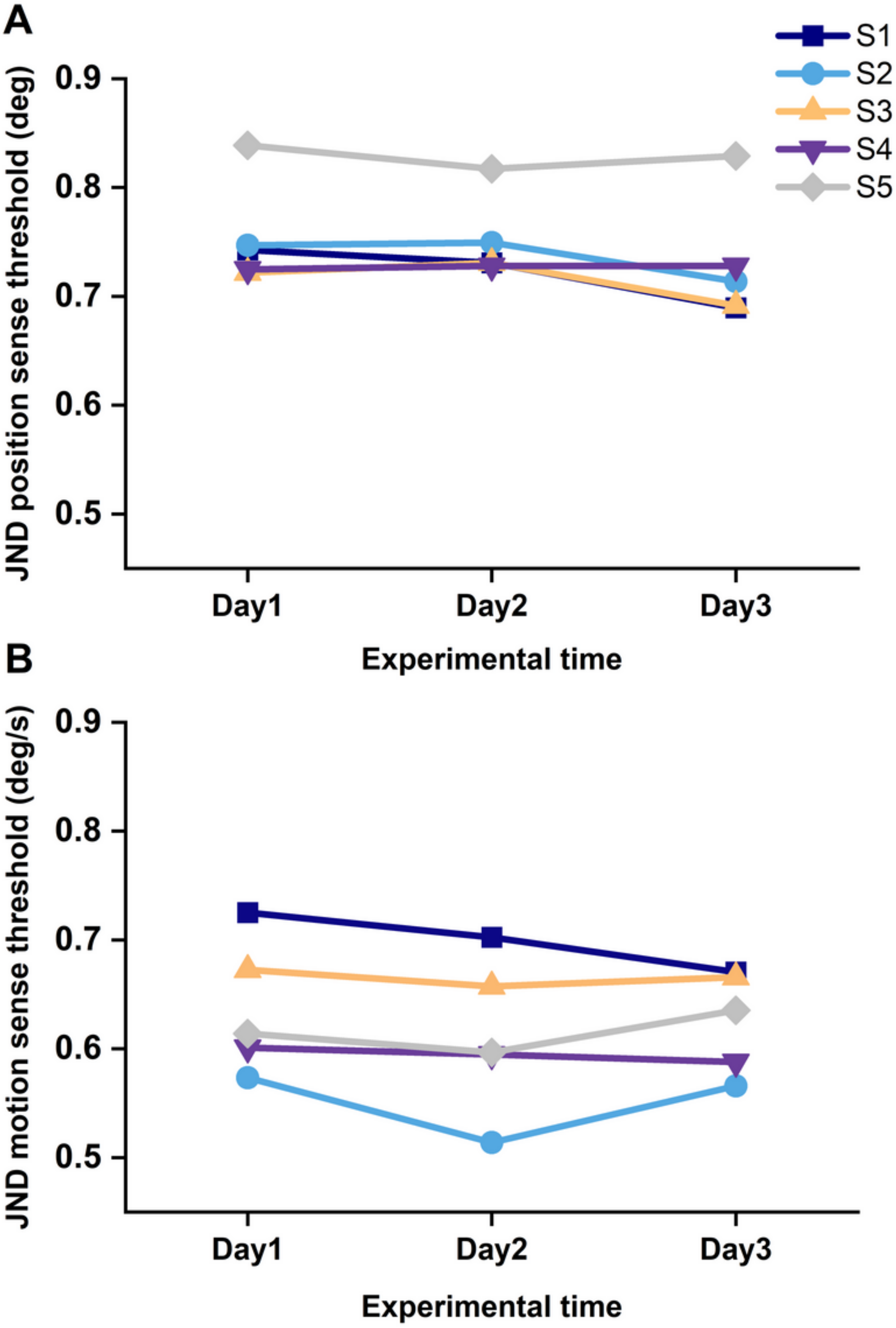

Figure 6

Test-retest reliability across three days in a subset of five subjects. **A**. JND position sense thresholds, and **B.** JND motion sense thresholds.