

# Quantifying Lower Limb Joint Position Sense Using a Robotic Exoskeleton: A Pilot Study

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**Abstract**— Clinicians and scientists often focus on tracking the recovery of motor skills after spinal cord injury (SCI), but less attention is paid to the recovery of sensory skills. Measures of sensory function are imperative for evaluating the efficacy of treatments and therapies. Proprioception is one sensory modality that provides information about static position and movement sense. Because of its critical contribution to motor control, proprioception should be measured during the course of recovery after neurological injury. Current clinical methods to test proprioception are limited to crude, manual tests of movement and position sense. The purpose of this study was to develop a quantitative assessment tool to measure joint position sense in the legs. We used the Lokomat, a robotic exoskeleton, and custom software to assess joint position sense in the hip and knee in 9 able-bodied (AB) subjects and 1 person with incomplete SCI. We used two different test paradigms. Both required the subject to move the leg to a target angle, but the presentation of the target was either a remembered or visual target angle. We found that AB subjects had more accurate position sense in the remembered task than in the visual task, and that they tended to have greater accuracy at the hip than at the knee. Position sense of the subject with SCI was comparable to those of the AB subjects. We show that using the Lokomat to assess joint position sense may be an effective clinical measurement tool.

**Keywords**—proprioception, assessment, rehabilitation, gait

## I. INTRODUCTION

In clinical settings, much effort has been placed into finding ways of restoring and tracking the recovery of voluntary motor function after spinal cord injury [1]. However, there is far less emphasis on doing the same for sensory function. Because motor function can be highly influenced by sensory information, it may be beneficial to improve sensory function in order to maximize overall motor recovery. Therefore, precise clinical assessments of sensory function are necessary to evaluate the effectiveness of treatments [2, 3]. Proprioception (static position sense and kinesthesia, or movement sense) is a sensory modality that is important for maintaining posture, locomotion [4], and motor learning [5], yet a reliable and precise method to measure proprioception in the lower limbs, especially one that could be used for neurological populations, is lacking.

There currently is no “gold standard” for clinical measurement of joint position sense in the lower limbs. Assessments of proprioception used by clinicians are not

quantitative and lack sensitivity [6]. For example, one clinical measure of joint position sense involves the clinician grossly moving a limb and asking the patient to simply indicate the direction that the limb was moved [7]. Another measure involves imitating a presented movement but quantification of the response is usually only estimated. More precise and sensitive methods to measure proprioception in clinical populations need to be developed and validated.

Several groups have developed methods to quantitatively measure proprioception in the upper extremities of able-bodied subjects for the purposes of basic research [8-12]. In addition, tools have been developed to quantitatively measure joint position sense in the upper extremity in persons with stroke [13-15] and hemiplegic cerebral palsy [16]. Wright and colleagues investigated how axial kinesthesia affected posture and locomotion in patients with Parkinson’s disease [17]. There are a small number of studies that quantitatively measure kinesthesia in the leg [18-22], and none of these studies involve neurological populations.

The purpose of our study was to develop a quantitative assessment tool of lower limb joint position sense using the Lokomat (Hocoma AG, Volketswil, Switzerland). Previously, the Lokomat has been used to assess voluntary muscle force and spasticity in the lower limbs [23, 24]. We used 2 different assessments to track lower limb proprioception at the hip and knee joint in able-bodied subjects and in 1 subject with incomplete SCI. Subjects had to move their hip or knee joint to a target angle when they were presented with either a remembered target (the subject’s joint was moved to the target angle and memorized, then moved away to a distractor position) or a visual target (a stick figure diagram configured into the target angle was displayed to the subject). The visual task eliminates the memory component of the remembered task, but subjects will be required to make a transformation of visual information into proprioceptive information. Testing these different paradigms will give a clearer picture of proprioceptive ability and help determine the ideal way to measure position sense in future studies.

## II. METHODS

### A. Subjects

Nine able-bodied subjects (3 males, 6 females; age (mean  $\pm$  SD) = 26.4  $\pm$  2.9 years, leg length (mean  $\pm$  SD) = 86.5  $\pm$  6.5

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cm) and 1 subject with incomplete SCI (1 male, age = 29 years, leg length = 94 cm, American Spinal Injury Association Impairment Scale (AIS) = B, level of injury = C6-C7, 7 years post-injury) participated in this study with informed, written consent. The SCI subject had abnormal sensation to pin-prick and light touch and primarily used a power wheelchair. Experimental procedures were approved by the Research Ethics Board at the University of British Columbia and were conducted in accordance with the Declaration of Helsinki.

## B. Equipment

### 1) Lokomat

We used the Lokomat, a robotic lower extremity exoskeleton, to quantitatively assess lower extremity proprioceptive function. The Lokomat is a computer-controlled motorized gait rehabilitation system consisting of a pair of robotic legs to which the thighs and lower legs are strapped. The thigh and shank segments of the Lokomat only allow movement in the sagittal plane and are moved by DC motors housed within the exoskeletal structure. Potentiometers within the exoskeleton measure the joint angles. The Lokomat was adjusted according to the length and size of the subject's legs. Subjects were secured to the Lokomat by leg cuffs around the mid-thigh, upper shank, and lower shank as well as a waist belt to provide trunk support. Each robotic leg attached to a central horizontal frame that secured the subject around the pelvis.

Subjects were attached to the Lokomat and suspended in an upright position above the ground using a body weight support system. This helped to ensure that the leg could move freely without touching the treadmill surface. The ankle of the test leg was fixed into a neutral position throughout the experiment with the use of passive foot lifter straps. The untested foot was placed onto a platform so that the subject could bear some weight on that leg for comfort. Foam padding was placed in between the straps and the skin on the lower leg to decrease any sensory cues from the straps as the leg was moved throughout testing.

The Lokomat moved the legs into predetermined positions and at fixed speeds using custom software. When subjects were asked to move their legs, they used a joystick controller to

change the hip or knee angles. This bypasses restrictions due to variations in the extent of voluntary control over the lower limb between individuals. We set the Lokomat to move the legs at 7° per second, except when using a joystick controller to move the legs, where the leg was set to move at 6° per second. We chose to use a different speed when using the joystick controller so that subjects would not use movement time as a cue to the location of the target position.

## C. Procedures

We used the Lokomat with our customized software to test 2 experimental paradigms for quantitatively assessing lower extremity joint position sense (Figure 1). Three hip angles (-10°, 10°, 30°) and three knee angles (20°, 40°, 60°) were used as target positions for a total of 9 combinations of angles. These angles were chosen because they spanned the range of motion typically used during walking. Only one joint was tested at a time, so each combination was done twice (the first time to assess the hip, the second time to assess the knee) within each of the 2 different assessment paradigms, resulting in 36 trials per subject. The order of angles tested was randomized within each task and joint tested. The dominant leg was tested in all able-bodied subjects. The more affected leg (right) was tested in the subject with SCI. Subjects were given breaks from the body weight support every 3-5 minutes. Throughout testing, vision of the legs was obscured with a curtain. Blood pressure was measured during the breaks to ensure it stayed near baseline values throughout the study. Joint angle data from the potentiometers were collected using custom software written in LabView (National Instruments, Austin, TX, USA).

### 1) Experiment 1. Remembered task

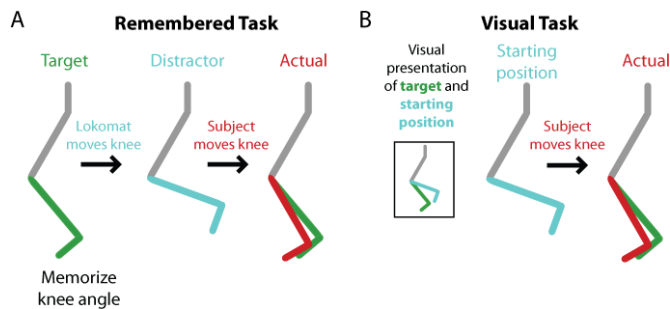
The dominant leg was moved into a target position and held there for 5 seconds. The subject was asked to memorize the angular position of the joint being tested (the hip or knee). The Lokomat then moved the test joint into another “distractor” position while the other joint was maintained in the same position. The subject was then asked to bring the test joint back into the memorized target position with the joystick controller. The final joint angle, or “actual” angle, was compared to the target angle and the difference was recorded as an error (Figure 1A).

### 2) Experiment 2. Visual task

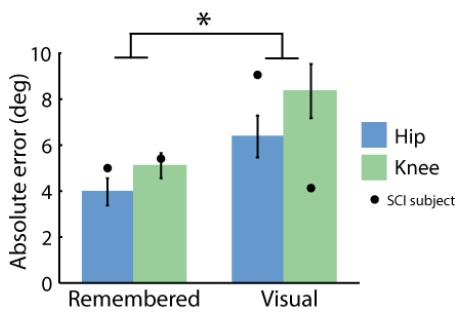
The subject's leg was moved by the Lokomat into a position that was 15-30° from the target position. The subject was then shown a stick figure of the starting position of the leg along with the target angle of the hip or knee, without any numerical indication of the angles. The untested joint did not change positions. No visual feedback of leg position was provided other than the static stick figure. The subject was then asked to bring the hip or knee into the target position with the joystick controller. The difference between the final actual angle and the target angle was recorded as an error (Figure 1B).

## Data analysis and statistics

Data was processed using custom programs written in MATLAB (Natick, MA, USA). At each target angle, we took the absolute values of all the errors. Smaller errors are



**Fig. 1.** Experimental protocol for the assessment of joint position sense in the Lokomat. A. Flow diagram for the Remembered task. The subject is placed into the target angle by the Lokomat and is asked to memorize the angle. After being moved away from the target, the subject uses a joystick to move the leg back to the target angle. B. Flow diagram for the Visual task. The visual presentation of the target angle and the starting angle is displayed to the subject. The subject is asked to use a joystick to move the knee into the target position.



**Fig. 2.** Absolute angle errors from able-bodied subjects for each joint during each task. Errors for the Visual task were significantly greater than those for the Remembered task (\* $P = 0.001$ ). There were no significant differences in errors between assessing the hip or the knee joint. The black dots are data from one SCI subject. Error bars represent  $\pm 1$  standard error of the mean (SEM).

associated with more accurate joint position sense. We averaged absolute errors for the hip and knee for both the Remembered and Visual tasks to compare differences across tasks. We also averaged the absolute errors at each hip target angle and each knee target angle to compare errors between the hip and knee.

Averaged raw values of the errors for each target angle were used to determine if errors tended to be towards flexion or extension for the hip and knee. Positive angles represent

flexion for both the hip and the knee.

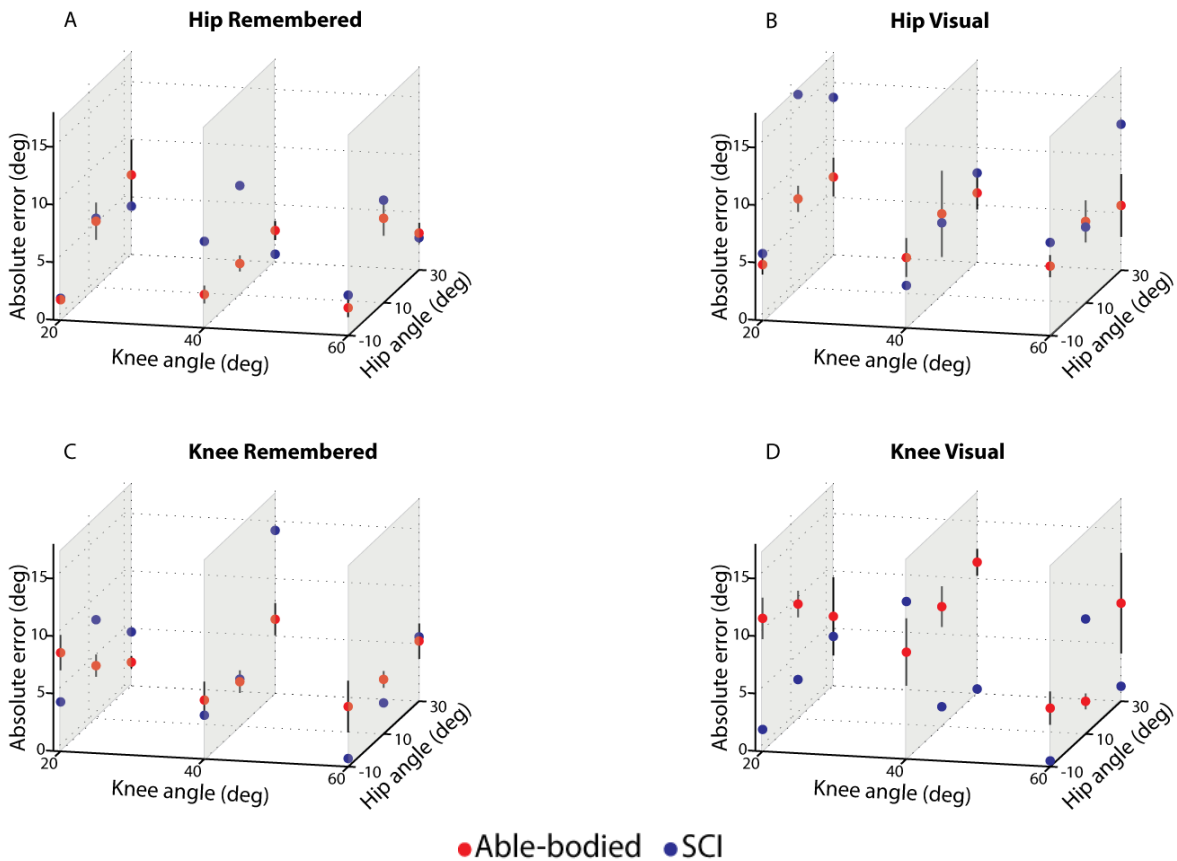
To determine if the tested joint angle and the untested joint angle together affected joint position accuracy, we compared averaged absolute errors across subjects for each joint angle combination within each task.

Data from the SCI subject was averaged across joint angles and plotted with the able-bodied subject data for visual comparison.

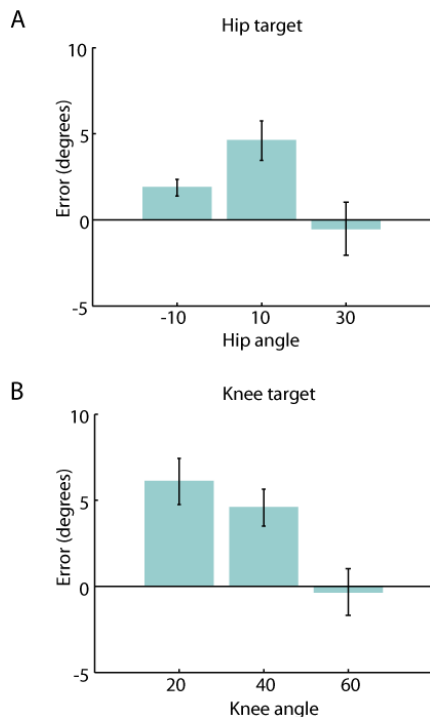
We performed a repeated measures analysis of variance (ANOVA) (2 tasks  $\times$  2 joints  $\times$  3 hip angles  $\times$  3 knee angles) comparing absolute errors. Post hoc analysis was performed as needed to delineate specific differences between groups (with a Sidak correction for multiple comparisons). All statistical analysis was performed using SPSS (Chicago, IL, USA). We ran the same analysis on the raw errors.

### III. RESULTS

Averaged absolute errors for the Remembered and Visual tasks at each position are shown in Fig. 2. There was a significant difference between the two tasks ( $P = 0.001$ ) (Remembered error =  $4.5^\circ \pm 0.54$  SE; Visual error =  $7.4^\circ \pm 0.53$  SE). The absolute errors tended to be larger at the knee than at the hip, but the differences were not significant ( $P = 0.130$ ) (Hip errors =  $5.2^\circ \pm 0.58$  SE; Knee errors =  $6.73^\circ \pm 0.72$



**Fig. 3.** Averaged absolute errors across able-bodied subjects for each condition and absolute errors from one SCI subject. There were no recognizable trends for errors across target angles and untested joint angles in the hip or the knee. Error bars represent  $\pm 1$  SEM.



**Fig. 4.** Raw errors averaged across subjects and tasks. Errors tended to be positive, except for when the knee and hip were most flexed. This indicates that errors tended to be into the direction of flexion for both the hip and knee joint assessments. Error bars represent  $\pm 1$  SEM.

SE). There were no significant differences due to target hip angle ( $P = 0.165$ ) or target knee angle ( $P = 0.115$ ). Absolute angle errors in the SCI subject were comparable to averages of the able-bodied subjects (SCI: Remembered error =  $5.5^\circ$ ; Visual error =  $6.6^\circ$ ).

There were no discernible trends of joint position accuracy based on either the hip or knee target angle in either joint or task (Fig. 3A-D).

Fig. 4A & B show averaged raw errors across subjects and tasks for the hip and knee. Errors tended to be in flexion (positive values), except for when the joints were most flexed and the average raw error was close to zero (errors occurred in the direction of both flexion and extension).

#### IV. DISCUSSION

The aim of this experiment was to establish the feasibility of using the Lokomat as a quantitative assessment tool of lower limb proprioception. We tested 2 different paradigms in order to help determine how to present the target angle to subjects. Our results showed that accuracy was significantly greater in the Remembered task than in the Visual task. Previous studies have shown that humans improve performance by integrating visual and proprioceptive information [25]. Based on this, it may be expected that subjects would have better results in the Visual task than in the Remembered task. However, visual information can only help to improve performance if it can be understood and used appropriately. In this experiment, an illustration of the leg's starting and target positions were presented to the subject while the leg was in the *starting*

*position*. The subject then had to transform the visual information into leg position, and had no knowledge of whether their usage of the visual information was correct or not. Subjects did not receive any information about their success at achieving the *target position*, so it would be difficult for them to know if they were using the visual information correctly. On the other hand, in the remembered task, subjects' legs were placed into the target position and therefore had accurate information about the *target* from proprioceptive afferent signals. In order to successfully move to the target position from the distractor position, they simply had to remember the sensations associated with the target position (assuming the sensors are accurate).

It is also possible that our form of visual presentation (a stick figure diagram of the starting and target position) was inadequate. A more dynamic visual representation that could give better context of the starting leg position in space may improve subject accuracy.

Results from the subject with SCI suggest that this is a feasible method of proprioceptive assessment in subjects with spinal cord injury. This subject was able to complete testing and able to use the joystick controller independently, even with compromised upper extremity function. The results of this subject were comparable to those of the able-bodied subjects. One notable difference is that the subject tended to have greater absolute errors at the hip than at the knee, which was opposite that of the able-bodied subjects.

##### A. Benefits and limitations of using the Lokomat

Robotic devices have recently been developed for the purposes of understanding the roles of sensory and motor function when making a desired movement. There is great potential for robotic devices to be useful in rehabilitation settings because of their capability to deliver high intensity and dosage of therapy and reliable measurement of performance [25, 26]. Upper extremity robotic manipulanda, such as the KINARM and InMotion, have been used to measure proprioception in the upper extremities in able-bodied subjects [9, 27] and in patients with stroke [14].

The Lokomat was initially developed to provide automated body-weight supported treadmill training to patients with neurological injury [28]. We were able to design custom software to control the Lokomat so that we could use it for the purpose of testing proprioception. There are several advantages of using the Lokomat with custom software for this type of assessment. The Lokomat is designed to fit people of different sizes and is fully adjustable, it contains several safety features so that it can be used with patients with neurological injury, its measurements of performance are accurate and reliable, and its motors can be programmed to move the legs precisely to specified positions and at specified speeds. With our software, subjects can move the legs with a joystick controller in order to account for variations in voluntary muscle strength. Legs can also be tested unilaterally, so that any difference in proprioceptive function between legs will not affect or confound results.

Another advantage of using the Lokomat to measure lower extremity proprioception is that participants can be tested in an

upright position, whereas most other tests of lower extremity proprioception occur in a seated or sidelying position [19, 22, 29, 30]. Testing lower extremity proprioception while standing is more functionally relevant than while sitting or lying down. It is also possible to maintain better control of positions of the “untested” joints using the Lokomat.

There are also some limitations to using the Lokomat for the assessment of proprioceptive function. The straps from the body weight support harness and exoskeleton may provide additional cutaneous feedback to the subject about joint position. We tried to prevent this by placing padding between the skin and the straps but completely eliminating this feedback would be difficult. In addition, prolonged suspension in body weight support often causes discomfort to subjects. We attempted to minimize this by having the subject bear weight on the untested leg and by giving rest from the body weight support throughout testing. The Lokomat can only control sagittal plane movement of the hips and knees, so it would not be possible to measure proprioception in any other plane, or in the ankle.

### B. Future studies

This study helped to show the feasibility of using the Lokomat to measure proprioception, but the validity and reliability of this tool must still be established. We plan to test more able-bodied subjects to determine normative data and also test more subjects with SCI across different levels of impairment to ascertain the viability of using this tool. We plan to also measure kinesthesia, or movement sense, by using the Lokomat to move the leg at a prescribed frequency and amplitude and having the subject replicate the same movement of the leg using the joystick controller. This tool could also be helpful for measuring proprioception of the lower limbs in other neurological populations, such as stroke and multiple sclerosis.

## V. CONCLUSIONS

In order to better characterize sensory deficits and track recovery after SCI, it is imperative to use more precise and quantitative assessment tools [2]. We showed that the Lokomat can potentially be a useful tool for the objective measurement of proprioception in the hip and knee joints. More testing is needed to establish the validity and reliability of this tool in neurological populations.

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