Current clinical practice in managing somatosensory impairments and the use of technology in stroke rehabilitation

Ananda Sidarta, Yu Chin Lim, Russell A. Wong, Isaac O. Tan, Christopher Wee Keong Kuah, Wei Tech Ang

1 Rehabilitation Research Institute of Singapore, Nanyang Technological University, Singapore, Singapore, 2 Lee Kong Chian School of Medicine, Nanyang Technological University, Singapore, Singapore, 3 Centre for Advanced Rehabilitation Therapeutics (CART), Tan Tock Seng Hospital, Singapore, Singapore, 4 School of Mechanical & Aerospace Engineering, Nanyang Technological University, Singapore, Singapore

* ananda.sidarta@ntu.edu.sg

Abstract

Stroke-induced somatosensory impairments seem to be clinically overlooked, despite their prevalence and influence on motor recovery post-stroke. Interest in technology has been gaining traction over the past few decades as a promising method to facilitate stroke rehabilitation. This questionnaire-based cross-sectional study aimed to identify current clinical practice and perspectives on the management of somatosensory impairments post-stroke and the use of technology in assessing outcome measures and providing intervention. Participants were 132 physiotherapists and occupational therapists currently working with stroke patients in public hospitals and rehabilitation centres in Singapore. It was found that the majority (64.4%) of the therapists spent no more than half of the time per week on somatosensory interventions. Functional or task-specific training was the primary form of intervention applied to retrain somatosensory functions in stroke survivors. Standardised assessments (43.2%) were used less frequently than non-standardised assessments (97.7%) in clinical practice, with the sensory subscale of the Fugl-Meyer Assessment being the most popular outcome measure, followed by the Nottingham Sensory Assessment. While the adoption of technology for assessment was relatively scarce, most therapists (87.1%) reported that they have integrated technology into intervention. There was a common agreement that proprioception is an essential component in stroke rehabilitation, and that robotic technology combined with conventional therapy is effective in enhancing stroke rehabilitation, particularly for retraining proprioception. Most therapists identified price, technology usability, and lack of available space as some of the biggest barriers to integrating robotic technology in stroke rehabilitation. Standardised assessments and interventions targeting somatosensory functions should be more clearly delineated in clinical guidelines. Although therapists were positive about technology-based rehabilitation, obstacles that make technology integration challenging ought to be addressed.
Introduction
Stroke is one of the leading causes of death and disability worldwide, where its burden has risen sharply from 1990 to 2019 [1]. About 86 million stroke survivors required rehabilitation services globally in 2019, higher than the number in 1990 by 85% [2]. Advances in medicine and healthcare have increased the survival rate, yielding a high number of people requiring long-term rehabilitation. For stroke survivors, motor impairments are often accompanied by deficits in limb position and movement senses or proprioception, which are important for motor control. About half of the stroke survivors typically experience loss of bodily sensation (somatosensation) in one or more modalities such as touch, position senses, temperature, and pressure [3–6].

Deficits in upper limb somatosensation are associated with reduced hand use and poorer sensorimotor integration, resulting in a decreased quality in fine motor control, object manipulation, and grip force regulation [7–10]. A patient holding a hot cup may be unable to perceive pressure and temperature optimally, resulting in increased danger of scalding. For the lower limb, impaired proprioception and light touch sensation have been found to impact gait speed [11, 12], limit independence in activities of daily living and the ability to balance [5, 13]. Therefore, disturbances in somatosensation result in, not only learned non-use of the affected limb, but also reduced emotional well-being, quality of life, and compromised safety [4, 7, 14]. Remarkably, somatosensory impairments usually receive less attention compared to the motor deficits which are relatively easier to assess and observe [15–17]. While clinicians generally believe that somatosensory impairment gradually recovers spontaneously, there are stroke survivors who are left with some degree of such deficits in the chronic phase beyond 6 months post stroke onset [18, 19]. Conducting somatosensory assessments can be challenging clinically, as it involves different sensory modalities which require long test routines. Not surprisingly, some prior work in the United States and Australia reported that not all therapists perform the standardised assessments and somatosensory-related interventions in their clinical practice [20, 21].

New technology has advanced healthcare and influenced how stroke rehabilitation can be delivered [22–24] to provide consistent, objective and motivational feedback. Some examples include upper limb robotic systems [25, 26], lower limb and balance training systems [27, 28], and wearable sensors [29]. In particular, robot-assisted therapy has been popular to deliver a higher dose of upper limb training which has been shown to provide moderate benefits [30]. Game-based virtual and augmented reality systems with motion sensing technology have also gained traction in rehabilitation. Microsoft Kinect (e.g. in [31]) or tablet games and applications (e.g. in [32]) can be used to deliver life-like task-based exercises. Another recent development is the application of non-invasive brain stimulation to enhance brain plasticity and restore balance in the cortical excitability post-stroke [33]. Considering the adoption of technology in stroke rehabilitation, its application as an assessment tool to evaluate recovery progression and changes in performances following an intervention period becomes attractive. Current clinical assessment systems employ ordinal scales that are known to be subjective and often unreliable due to low sensitivity [34, 35]. In contrast, modern machines are capable of giving a more precise and objective evaluation of patient progress. Some studies, however, still suggest that the adoption of technology by the therapists for stroke rehabilitation is found to be lacking [36, 37].

In this study, we sought to understand the perspectives and opinions of therapists in Singapore concerning standard practices in managing somatosensory impairments. Here, ‘to manage’ was used to mean both assessment (of impairment) and intervention (e.g., training or therapy sessions, exercises). Results from this study would be beneficial to identify the gap
between the current practice and evidence-based recommendations. We also examined the adoption of different types of rehabilitation technology and how well it had been integrated in the clinical setting. Focus was given to the application of robotic systems for proprioceptive interventions. Lastly, the study also identified obstacles to implementing technology in clinical practice.

**Materials & methods**

**Design**

A questionnaire-based cross-sectional study was conducted with occupational therapists and physiotherapists working in stroke rehabilitation across various healthcare settings in Singapore. An online, self-administered anonymous questionnaire was carried out between August 2021 and February 2022. The reporting of this study adheres to established standards for reporting web-based surveys, the Checklist for Reporting Results of Internet E-Surveys (CHERRIES) [38]. The study was approved by the Institutional Review Board of Nanyang Technological University, Singapore (protocol number: IRB-2020-10-012).

**Materials**

The questionnaire was developed by the research team and adapted from prior studies [20, 37] that aimed to determine somatosensory assessment and treatment used by the therapists for stroke survivors, and the type of technology employed in stroke rehabilitation programmes. All items within the questionnaire were evaluated and refined by an occupational therapist and a physiotherapist who were part of the research team. The final questionnaire distributed using the web-based application Microsoft Forms consisted of 21 question items divided into four sections. Of the 20 closed-ended questions, six allowed the participants the chance to provide further details if ‘other’ or ‘unsure’ option was selected. The response options for closed-ended questions varied from single- or multiple-select choice type to 5-point Likert (from strongly disagree to strongly agree) or frequency rating scale ranging from not available to regularly (defined as >5 times a week). One open-ended question was created for the participating therapists to elaborate their thoughts regarding the overall topic of the questionnaire.

The first section included demographic questions regarding therapists’ length of experience in stroke rehabilitation, practice setting, and proportion of time spent with stroke survivors. The second section dealt with the management of somatosensory impairment in routine clinical practice. This included questions on the types of intervention and assessment frequently applied and the usage frequency of common somatosensory-related interventions. In this questionnaire, somatosensory intervention referred to any targeted forms of training or exercise that aim at improving somatosensation. For example, tactile (e.g., touch discrimination of textures) or object (e.g., recognition of solid objects) discrimination, training of proprioception (e.g., position sense, identifying direction of limb movements), thermal stimulation, compression therapy using pneumatic compression devices and garments, and electrical or magnetic stimulation including but not limited to TENS (transcutaneous electrical nerve stimulation) and rPMS (repetitive peripheral magnetic stimulation). As somatosensation appears to be essential for balance control, any balance-related exercises were considered for inclusion. Repetitive practice of active movements, and functional training that involves sensorimotor integration such as fine motor control and postural adjustment were also regarded as being relevant.

Ratings of the perceived clinical importance of proprioception in stroke rehabilitation were covered in the third section. The last section explored therapists’ views and experiences of using technology in stroke rehabilitation, in particular for retraining proprioception. Here,
‘rehabilitation technology’ was defined as innovations in machines or devices which help to maximise functions and reduce impairments, and at the same time, provide objective assessment in stroke rehabilitation. The predefined lists of equipment and technology options in this section were determined based on their common appearance in the rehabilitation research and to cover a broad set of possible options. A question on the main barriers and obstacles to incorporating technology into rehabilitation practice was also asked in the latter part of the section.

Recruitment
Licensed occupational therapists and physiotherapists, who were actively involved in working with stroke survivors in Singapore, with at least 1-year of clinical experience were recruited by purposive sampling. In total, 15 public hospitals and rehabilitation centres in Singapore were approached for this survey. All participating therapists were enrolled through contact with the Head of Department, clinical supervisors, or senior therapists, where these points-of-contact served as an interface between the research team and the eligible participants. There was no direct contact between the researchers and therapists to ensure anonymity.

Procedure
The points-of-contact were initially provided with a verbal outline of the study. Once they expressed interest and agreed to assist the research team in recruiting the occupational therapists and physiotherapists in their department, a brief recruitment message with study background, inclusion criteria, and a web link (URL) to the questionnaire was sent to them via emails or WhatsApp text messages. The message was then circulated within the respective department to invite those who fulfilled the inclusion criteria to take part. The therapists were allowed to complete the questionnaire in their own time and were informed that all questions were optional, and their participation was completely voluntary. Consent for participation was obtained online via the same web link prior to starting the questionnaire. Gift vouchers prepared by the research team as incentives for participation were handed out by points-of-contact to the therapists upon completion of the questionnaire.

Data analysis
The questionnaire responses were extracted and input into SPSS statistical software, version 28 (IBM Corp., Armonk, N.Y., USA) for coding and analysis. All nominal and ordinal data were analysed using frequency. The response percentage did not always sum to 100% as participants were allowed to select multiple answers and skip questions which they were not comfortable answering (the overall percentage of missing values was 1.1%). All open-ended responses were reviewed and independently coded into predefined categories by two coders from the research team. Any discrepancies in the coding were resolved through discussion. Coded responses to ‘other’ items were included in the frequency analysis as mentioned above. Therapists’ verbatim comments that were deemed relevant and useful to explain or support the results were presented in the main text, together with their case number as denoted by ‘PN. xx’ in brackets. Questionnaire responses were stored in a secured harddrive that could only be accessed by the principal investigator and the research team who performed the analysis.

Results
A total of 132 participants from 13 healthcare sectors completed the questionnaire. On average, it took 18.34 minutes for them to go through all questions, and none terminated the
questionnaire early. The participants were between the ages of 23 and 54 (M = 32.38, SD = 5.93; 109 females), comprising 56.1% (n = 74) physiotherapists and 43.9% (n = 58) occupational therapists. The average work experience in stroke rehabilitation was 6.58 years (SD = 5.21). A Mann-Whitney U test indicated that no differences were observed in age (U = 1849, p = .293) and years of experience (U = 1929.50, p = .404) between physiotherapists and occupational therapists. Many of them (45.5%, n = 60) work in acute or restructured hospitals, followed by day rehabilitation centres (28%, n = 37), community hospitals (12.9%, n = 17), and nursing homes (8.3%, n = 11). About half (50.8%, n = 67) of the therapists work in an inpatient care setting, and most (35.6%, n = 47) provided rehabilitation services to patients with subacute and chronic stroke. The complete demographic characteristics of the participating therapists are illustrated in Table 1.

Table 1. Participants demographic characteristics.

| Characteristic                 | n   | %    | M   | SD  |
|-------------------------------|-----|------|-----|-----|
| Age                           | 32.38 | 5.93 |
| Years of experience in stroke care | 6.58 | 5.21 |
| Gender                        |     |      |     |     |
| Female                        | 109 | 82.6 |
| Male                          | 23  | 17.4 |
| Profession                    |     |      |     |     |
| Occupational therapist        | 58  | 43.9 |
| Physiotherapist               | 74  | 56.1 |
| Practice setting              |     |      |     |     |
| Inpatient                     | 67  | 50.8 |
| Outpatient                    | 63  | 47.7 |
| Health facility               |     |      |     |     |
| Acute or restructured hospital | 60  | 45.5 |
| Community hospital            | 17  | 12.9 |
| Day rehabilitation centre     | 37  | 28.0 |
| Nursing home                  | 11  | 8.3  |
| Other                         | 6   | 4.5  |
| Regional healthcare cluster   |     |      |     |     |
| Central                       | 46  | 34.8 |
| West                          | 31  | 23.5 |
| East                          | 20  | 15.2 |
| Multiple, nationwide          | 35  | 26.5 |
| Client type                   |     |      |     |     |
| Acute                         | 17  | 12.9 |
| Subacute                      | 28  | 21.2 |
| Chronic                       | 19  | 14.4 |
| Acute and subacute            | 11  | 8.3  |
| Subacute and chronic          | 47  | 35.6 |
| All types                     | 9   | 6.8  |
| Stroke care service time      |     |      |     |     |
| <25%                          | 41  | 31.1 |
| 26–50%                        | 35  | 26.5 |
| 51–75%                        | 29  | 22.0 |
| >75%                          | 27  | 20.5 |

https://doi.org/10.1371/journal.pone.0270693.t001
Management of somatosensory impairment

Various types of training or interventions typically performed in the clinics to improve somatosensory functions in stroke survivors can be seen in Fig 1. Functional or task-specific training (99.2%, n = 131) was shown to be the most popular form of exercise, followed by movement-based exercises (89.4%, n = 118), and balance-related training (79.5%, n = 105). Regardless of the stroke phase, these were the three most common interventions delivered across patients to retrain their somatosensory functions. The therapists also reported the use of somatosensory-focused approaches: proprioception (59.8%, n = 79), object discrimination or recognition (41.7%, n = 55), tactile-based exercises (40.2%, n = 53), use of compression (14.4%, n = 19), and thermal stimulation (12.9%, n = 17). Over half (54.5%, n = 72) also indicated employing electrical or magnetic stimulation. One therapist who selected ‘other’ option reported the use of splinting as another method of intervention.

Approximately two-thirds of the therapists (64.4%, n = 85) spent half of their time or less providing somatosensory interventions to stroke survivors with somatosensory impairment, and only 34.1% (n = 45) spent more than half of their time per week. Two were unsure of how much time they spent on such training every week. When asked to report the usage frequency of certain intervention approaches earlier mentioned, the majority (72.7%, n = 96) of them reported conducting functional training regularly (more than five times a week), 18.2% (n = 24) at least two times per week, and 6.1% (n = 8) rarely (less than two times per week). With regards to electrical or magnetic stimulation, only 9.8% (n = 13) implemented it regularly, 28.8% (n = 38) sometimes, and 45.5% (n = 60) rarely. Further, a small proportion of the therapists (16.7%, n = 22) stated that they delivered proprioceptive training regularly, 43.2% (n = 57) sometimes, and 27.3% (n = 36) rarely. Similarly, tactile based exercises were applied regularly by only a few therapists (6.1%, n = 8), sometimes 23.5% (n = 31), and rarely 50.8% (n = 67).

![Fig 1. Different forms of somatosensory-related intervention used in clinics.](https://doi.org/10.1371/journal.pone.0270693.g001)
In terms of the standard clinical evaluation for somatosensation, the sensory scale of the Fugl-Meyer Assessment was employed by one-third of the therapists (32.6%, \(n = 43\)). Surprisingly, only a small minority employed the Nottingham Sensory Assessment (5.3%, \(n = 7\)), Rivermead Assessment of Somatosensory Performance (3.8%, \(n = 5\)), and Semmes-Weinstein Monofilament Test (2.3%, \(n = 3\)). Generally, non-standardised outcome measures were preferred by the overwhelming majority of them (97.7%, \(n = 129\)), as opposed to the standardised assessment tools mentioned above. As illustrated in Table 2, the two most frequently used non-standardised tests were light touch (72.9%, \(n = 94\)) and position sense (66.7%, \(n = 86\)), followed by pain (39.5%, \(n = 51\)), pressure (34.9%, \(n = 45\)), sensory extinction (33.3%, \(n = 43\)), and stereognosis (26.3%, \(n = 34\)). In addition to the sensory modalities provided, three reported the evaluation of coordination, sharp-blunt discrimination, and thermal sensation through non-standardised measures.

### Technology adoption in stroke rehabilitation

The adoption of rehabilitation technology as part of regular clinical care is still fairly limited. Only about one-third (31.8%, \(n = 42\)) of the therapists had more than 3 years of experience in using rehabilitation technology, mainly in the inpatient setting (64.3%, \(n = 27\)) with patients in the subacute and chronic stroke phases (35.7%, \(n = 15\)). More than half (52.3%, \(n = 69\)) reported that they had fewer than 3 years of experience with rehabilitation technology, and about 16% (\(n = 21\)) had no experience (Fig 3(a)). Spearman's rank-order correlation found a moderate positive relationship between the therapists’ years of experience in stroke care and with rehabilitation technology, \(\rho (129) = .53, p < .001\), denoting that those who were more experienced usually had greater exposure to rehabilitation technology.

Although most therapists had little to no experience with rehabilitation technology, most still reported having access to certain forms of technology in their practice settings. Nearly all (95.5%, \(n = 126\)) stated that electrical stimulation devices were available to them, but less than half (48.4%, \(n = 61\)) used such devices two or more times per week and 51.6% (\(n = 65\)) rarely or never used them. The next most widely available forms of technology were virtual reality and commercial gaming systems (63.6%, \(n = 84\)), which were more accessible to those who

### Table 2. Types of standardised and non-standardised assessment of somatosensation.

| Standardised                                      | \(n\) | %   |
|--------------------------------------------------|-------|-----|
| Fugl-Meyer Assessment of Sensation               | 43    | 32.6|
| Nottingham Sensory Assessment                    | 7     | 5.3 |
| Rivermead Assessment of Somatosensory Performance| 5     | 3.8 |
| Semmes-Weinstein Monofilament test               | 3     | 2.3 |
| Non-standardised test                            | 129   | 97.7|

| Non-standardised                                 | \(n\) | %   |
|--------------------------------------------------|-------|-----|
| Light touch                                      | 94    | 71.2|
| Position sense                                   | 86    | 65.2|
| Pain                                             | 51    | 38.6|
| Pressure                                         | 45    | 34.1|
| Sensory extinction                               | 43    | 32.6|
| Stereognosis                                     | 34    | 25.8|
| Other                                            | 3     | 2.3 |

Note. Participants were allowed to select multiple answers.

https://doi.org/10.1371/journal.pone.0270693.t002
work in acute or restructured hospitals (50%, \( n = 42 \)) and day rehabilitation centres (25%, \( n = 21 \)). However, just over a quarter (26.2%, \( n = 22 \)) of the therapists used them on a regular basis, and most (69%, \( n = 58 \)) fewer than twice a week or never. Additionally, the proportion of therapists who stated having access to upper limb assistive technologies (47.7%, \( n = 63 \)) was comparable to those who had access to lower limb assistive technologies (52.3%, \( n = 69 \)).

While upper limb assistive technologies were more accessible to those from acute or restructured (47.6%, \( n = 30 \)) and community hospitals (22.2%, \( n = 14 \)), assistive technologies for lower limb were more available to acute or restructured hospitals (55.1%, \( n = 38 \)) and day rehabilitation centres (21.7%, \( n = 15 \)). Both upper and lower limb assistive technologies were used at least two times a week by only 28.6% (\( n = 18 \)) and 33.3% (\( n = 23 \)) of the therapists, respectively. Few (5.3%, \( n = 7 \)) reported having access to multicomponent technology that provides simultaneous training of different functioning abilities such as balance, cognition, and mobility.

Rehabilitation technology was employed primarily for intervention (87.1%, \( n = 115 \)) compared to assessment (30.3%, \( n = 40 \)). As presented in Fig 2, the most frequently reported technology-based intervention provided to stroke survivors was lower extremity movement (45.5%, \( n = 60 \)), followed by upper extremity movement (42.4%, \( n = 56 \)), balance (39.4%, \( n = 52 \)), cognition (31.1%, \( n = 41 \)), functional activities (28%, \( n = 37 \)), and sensation (14.4%, \( n = 19 \)). By contrast, technology was used by a relatively small proportion of the therapists to assess lower extremity movement (12.1%, \( n = 16 \)), balance, cognition (both 10.6%, \( n = 14 \)), upper extremity movement (9.8%, \( n = 13 \)), functional activities (8.3%, \( n = 11 \)), and sensation (1.5%, \( n = 2 \)). Further analysis revealed that occupational therapists tended to incorporate technology in their practice to retrain upper limb and cognitive functions, whereas

![Fig 2. Adoption of technology for the purpose of either assessment or intervention. The number of responses did not always sum to 132 as participants were allowed to select multiple answers.](https://doi.org/10.1371/journal.pone.0270693.g002)
physiotherapists conducted technological intervention targeting lower limb functions and balance (see Fig F in S4 File).

Perceived barriers to integrating robotic technology in clinical practice

A majority (89.4%, n = 118) of the participating therapists regarded price as the main barrier to the successful integration of robotic technology in clinical practice (see Fig 3(b)). Nearly all who work in the day rehabilitation centres (91.9%, n = 34), acute or restructured hospitals (90%, n = 54), and nursing homes (90.9%, n = 10) considered this the biggest implementation obstacle. Usability of technology or ease of use was identified by almost three-quarters (73.5%, n = 97) of the therapists as the next most common barrier. This was followed subsequently by lack of space (68.9%, n = 91), inadequate technical support (59.1%, n = 78), and patient’s needs (43.2% (n = 57). Of particular note was most therapists (88.2%, n = 15) who work in the community hospitals ranked usability higher than price as the top barrier to implementation. Lack of available space was another challenge faced by 76.5% (n = 13) of those from community hospitals, which was of equivalent rank to price. On the other hand, inadequate technical support was one of the most common obstacles that prevent most therapists working in day rehabilitation centres (75.7%, n = 28) and nursing homes (63.6%, n = 7) from adopting robotic technology for rehabilitation. In addition to the predetermined list of options, some therapists mentioned that patient mobility, insufficient funding, and long setup time would affect the effective implementation of robotic technology.

Additional comparative analyses were conducted to examine therapists’ views and practices on somatosensory assessment and intervention, as well as the adoption of technology in different regional healthcare clusters. Analyses in terms of speciality (physical therapist or occupational therapist) were also included. The full results can be seen in the “Supporting Information, S4 File”.

Perceived role of retraining proprioception and robot-assisted rehabilitation

A general positive evaluation of statements regarding the clinical importance of proprioceptive rehabilitation and the application of robotic technology in rehabilitation, particularly in proprioceptive retraining, is depicted in Fig 4. This is indicated clearly by considering the
combined totals of the agree and strongly agree categories. A reliability analysis showed that the reliability and inter-item consistency were acceptable, $\alpha = 0.83$. The Cronbach’s alpha of all items would not increase with the exclusion of any item, and thus no removal of items should be considered.

Fig 4(a) shows that most of the therapists (82.6%, $n = 109$) agreed that proprioceptive training can help to improve motor function following a stroke and is essential for patients with sensory impairment. This suggests that most therapists understood the benefits of retraining proprioception due to its impact on motor function, especially in stroke survivors with sensory loss. Further, 78% ($n = 103$) of them thought that an effective and highly repetitive intervention is beneficial to stroke patients, and there were more of them (82.6%, $n = 109$) appreciated the
idea of an objective and reliable assessment of proprioception. In addition, 78% (n = 103) of therapists agreed that it is important to track and monitor the improvement of proprioception over time.

While most believed that an effective and highly repetitive intervention is clinically beneficial, 79.5% (n = 105) of the therapists agreed that such an intervention can be achieved through robotic therapy (see Fig 4(b)). Although not as high as those who were in favour of robotic therapy, 60.6% of them (n = 80) still considered that robotic-based assessments are objective and reliable. One physiotherapist seemed to appreciate technology-based rehabilitation due to its ability to lighten the workload of therapists, allowing them to focus on observing patients’ performance and offering constructive feedback (PN. 2). By contrast, another physiotherapist thought that technology is unsuitable for patients with cognitive impairments and muscle weakness (PN. 88). Interestingly, 81% (n = 70) of the therapists believed that robotic therapy combined with conventional therapy can be more effective than conventional therapy alone. This was echoed by one participant (PN. 20) who elaborated, “Technology needs to be used adjunct to conventional therapy and not in isolation to ensure carryover of skills,” indicating that robotic technology is more likely to be adopted in interventions by combining it with conventional rehabilitation methods. This general level of agreement among the therapists further implies that most (77.3%, n = 102) believed robot-assisted therapy can keep patients motivated and engaged. Despite this, when asked whether robotic technology would be beneficial for retraining proprioception, 65.2% (n = 10) of them agreed (Fig 4(c)). One of them who did not share any opinion on this pointed out having a lack of knowledge of technology-based intervention options for somatosensory impairment (PN. 41). Moreover, therapists’ opinion on employing rehabilitation programmes with integrated motor and sensory components was particularly strong, as 91.7% (n = 107) of them believed that this would benefit the patients.

Discussion

Stroke survivors require long-term rehabilitation to cope with their impairments and be independent in the community and home. People with stroke typically experience both motor and somatosensory impairments, but past literature suggests that somatosensory components receive lesser attention. Existing interventional studies that target somatosensory loss are still rather limited. One potential reason is the greater emphasis on movement-related interventions to regain functional independence, which are more widely studied and have observable benefits [17, 39, 40]. Another possible explanation is that therapists have inadvertently integrated somatosensory components into their daily rehabilitation routines, without targeting any specific sensory modalities. The findings in the second section of the questionnaire are in line with these arguments.

Therapists in the current study predominantly and regularly applied functional or task-specific training as the primary forms of somatosensory intervention. Movement-based exercises and balance training were reported to be the next most popular forms of intervention. Although these exercises simultaneously engage in sensory integration and postural control, they can be considered ‘motor training’. And as highlighted by two participating therapists, motor improvements are more important than somatosensory aspects for functional independence (PN. 23, 97). On other hand, interventions focusing on sensations of touch (discerning roughness, pressure, or vibration) and temperature were less commonly implemented. This is interesting given that those types of sensory perception are arguably important for motor control and safety during movement. It is possible that stroke survivors with somatosensory deficits served by the participating therapists were of a small number. However, even if somatosensory intervention is required for some patients, most participants still spent less
than 25% of their clinical practice time providing targeted exercises. Two therapists who were unsure of their time spent on such intervention stated that other types of training intervention tend to take precedence over somatosensory interventions when somatosensory loss appears as a secondary impairment (PN. 97, 99). This is despite some evidence-based studies for more targeted interventions to retrain impaired tactile, proprioception, and other modalities [6, 39, 41, 42]. If present, such forms of targeted exercise are typically combined with functional or task-specific activities to effectively stimulate and strengthen post-stroke motor recovery in patients with motor and somatosensory deficits [43–46].

The current study found that the majority of therapists favoured non-standardised clinical measures for assessing somatosensory impairment. This corroborates another finding obtained in earlier surveys that examined the use of standardised somatosensory assessments in adult stroke survivors and children with neurological disorders [20, 21, 47]. These few studies revealed that the standardised assessments of somatosensation are underutilised. Evidence regarding the use of validated and reliable instruments by therapists in stroke rehabilitation varies across countries [48–51]. For example, the use of standardised assessments was notably high in the United Kingdom but relatively low in Canada, likely due to lack of time and knowledge about outcome measures. Although standardised outcome measures are commonplace in certain countries, international and local consensus regarding which instruments to use in practice is limited [49, 50]. This suggests that recommendations on the selection of valid and reliable outcome measures for stroke rehabilitation appear to be vague, hence non-standardised assessments were widely administered by therapists in the present study.

The two most common non-standardised assessments reported by the current participants are consistent with the results reported by Winward et al. [16], Doyle et al. [21], and Pumpa et al. [20], where light touch and proprioception were mostly assessed. Among the standardised clinical scales, the Fugl-Meyer Assessment having both motor and sensory subscales is widely used in practice to evaluate sensorimotor impairments post-stroke [52, 53]. This interesting finding is consistent with the idea that the Fugl-Meyer Assessment is considered holistic, and thus commonly adopted as part of the typical clinical assessments for the stroke population. While the Nottingham Sensory Assessment is a recommended and more detailed measure of various sensory deficits [54, 55], it was used less frequently than the sensory subscale of the Fugl-Meyer Assessment in this study. In fact, the original Nottingham Sensory Assessment with the application of specialist equipment is time-consuming and known to have poor inter-rater reliability; accordingly further revisions were made to improve the reliability and to reduce testing time [56]. Lastly, the Semmes-Weinstein Monofilament Test, which is found to be most frequently used by therapists in Australia [20], was the least popular among the provided standardised assessments.

The third section of the questionnaire explored participants’ views towards proprioception, one of the specific somatosensory modalities which has been demonstrated to contribute greatly to motor control and learning. Unlike the work by Winward et al. that examined the clinicians’ view on the importance of somatosensory assessment as a whole [16], we had a closer look at the interventional aspects of proprioception. Overall, participants in this study were positive about how proprioceptive intervention improves motor functions after stroke, particularly for those suffering from sensory impairment. This is consistent with recent training or exercise protocols which target proprioception and tactile senses [41, 57, 58]. In conjunction, the therapists also agreed strongly that an objective and reliable assessment would be useful to inform performance and track or monitor recovery progression. These could be achieved or facilitated by a highly repetitive rehabilitation programme with the use of robotic technology, which was agreeable to most therapists as shown in the final section of the questionnaire (Fig 4). Indeed, robot-assisted therapy has shown great promise, and recent studies
targeting proprioception have been proposed to address such dysfunction in the stroke population, e.g. as described in [59–61].

Most therapists demonstrated a strong preference for adopting rehabilitation technology for intervention. On the contrary, fewer agreed with the idea of technological-based assessment. This finding is in line with a recent study of American therapists being more likely to use technology for intervention than assessment [37]. Despite the recent development of robotic-based assessment systems [34, 62, 63], the acceptance of using these devices in clinical practice is still scarce, with one therapist explaining that assessment data generated are typically laborious to interpret, and thereby are impractical to inform clinical decision and progression (PN. 44). Such statements show that there is still much room for improvement in technology before there is widespread implementation. Another potential challenge is to develop a rehabilitation device that can evaluate the heterogeneous nature of somatosensory performance, including the discrimination and detection ability (PN. 54).

Rapid advances and innovation in robotic technology can address unmet challenges in rehabilitation in Singapore [23]. However, high price was perceived by the therapists to be the topmost barrier to integrating technology regardless of the practice setting. This finding echoed similar obstacles to integration identified in the previous study. For example, in a mixed methods survey, Li et al. identified perceived logistical issues (ease of use, storage space) and cost as the major factors in the United Kingdom [64]. Nonetheless, at least two studies suggest that robot-assisted rehabilitation does not significantly incur higher costs in the long run as compared to the conventional care [65, 66]. Therapists usually prefer technology that is easy to use, invokes less time to prepare, and compact (PN. 20, 44, 54, 113, 115). It would be worth noting that having a robotic system that can provide diverse assessment of somatosensory modalities makes more economical sense. Overcoming logistical issues would involve resource planning and cost-benefit analysis, which requires heavy discussion among stakeholders, such as healthcare managements and technology companies. This ensures that any robotic system developed can be translated into proper clinical use, such as in bedside testing or in telerehabilitation.

Conclusions

This work determined the current clinical practice and perceptions in managing somatosensory impairment and implementing rehabilitation technology in stroke care within Singapore. Somatosensory-specific interventions and standardised assessments were rarely implemented in clinical practice. The current findings showed that technological applications in rehabilitation were more apparent in intervention than in assessment. Therapists believed that intensive training of proprioception and objective assessments are beneficial and critical to stroke recovery. Robotic technology can be seen as a way to promote standardisation in somatosensory assessments and to deliver more effective interventions. However, technology was rarely adopted for targeted sensory interventions by the participants. Lastly, price, ease of use, and space availability were viewed as the top three main obstacles to technology integration in clinical practice.

There are certain aspects of this study that warrant future investigation. Self-administered closed ended questions may limit responses and opinions and can lead to different interpretations of wording among different participants. Hence, methods such as focus group interviews with open ended questions can be employed as a follow-up study. Clinical guidelines that contain recommendations to promote more targeted training and standardised measures of somatosensory functions can also be developed. Technological innovation can change the rehabilitation landscape, but some real-world obstacles and barriers cannot be neglected. This
study was not designed to better understand customer needs or to increase the utilization rate of certain robotic technology. Therefore, more studies and evidence are vital to examine if the long-term benefits will outweigh the perceived obstacles.

**Supporting information**

S1 File. Questionnaire.  
(PDF)

S2 File. CHERRIES checklist.  
(DOCX)

S3 File. Coded data.  
(XLSX)

S4 File. Additional analyses.  
(DOCX)

**Author Contributions**

**Conceptualization:** Ananda Sidarta, Isaac O. Tan, Christopher Wee Keong Kuah, Wei Tech Ang.

**Data curation:** Ananda Sidarta.

**Formal analysis:** Yu Chin Lim, Russell A. Wong, Isaac O. Tan.

**Funding acquisition:** Ananda Sidarta, Wei Tech Ang.

**Methodology:** Ananda Sidarta, Yu Chin Lim, Christopher Wee Keong Kuah.

**Project administration:** Yu Chin Lim, Russell A. Wong.

**Supervision:** Ananda Sidarta, Christopher Wee Keong Kuah.

**Writing – original draft:** Ananda Sidarta, Yu Chin Lim, Russell A. Wong, Isaac O. Tan.

**Writing – review & editing:** Ananda Sidarta, Yu Chin Lim, Isaac O. Tan.

**References**

1. Feigin VL, Stark BA, Johnson CO, Roth GA, Bisignano C, Abady GG, et al. Global, regional, and national burden of stroke and its risk factors, 1990–2019: A systematic analysis for the Global Burden of Disease Study 2019. The Lancet Neurology. 2021;20(10):795–820. https://doi.org/10.1016/S1474-4422(21)00252-0 PMID: 34487721

2. Cieza A, Causey K, Kamenov K, Hanson SW, Chatterji S, Vos T. Global estimates of the need for rehabilitation based on the Global Burden of Disease study 2019: a systematic analysis for the Global Burden of Disease Study 2019. The Lancet. 2020;396(10267):2006–17. https://doi.org/10.1016/S0140-6736(20)32340-0 PMID: 33275908

3. Carey LM, Matyas TA. Frequency of discriminative sensory loss in the hand after stroke in a rehabilitation setting. Journal of rehabilitation medicine. 2011;43(3):257–63. https://doi.org/10.2340/16501977-0662 PMID: 21305243

4. Carey LM, Matyas TA, Baum C. Effects of Somatosensory Impairment on Participation After Stroke. Am J Occup Ther. 2018;72(3):7203205100p1-p10. https://doi.org/10.5014/ajot.2018.025114 PMID: 29869179

5. Tyson SF, Crow JL, Connell L, Winward C, Hillier S. Sensory impairments of the lower limb after stroke: a pooled analysis of individual patient data. Top Stroke Rehabil. 2013;20(5):441–9. https://doi.org/10.1310/ts2005-441 PMID: 24091286

6. Schabrun SM, Hillier S. Evidence for the retraining of sensation after stroke: a systematic review. Clin Rehabil. 2009;23(1):27–39. https://doi.org/10.1177/0269215508098897 PMID: 19114435
7. Yekutiel M. Sensory re-education of the hand after stroke: John Wiley & Sons Incorporated; 2000.
8. Nowak DA, Grefkes C, Dafotakis M, Küst J, Karbe H, Fink GR. Dexterity is impaired at both hands following unilateral subcortical middle cerebral artery stroke. Eur J Neurosci. 2007; 25(10):3173–84. https://doi.org/10.1111/j.1460-9568.2007.05551.x PMID: 17561831
9. Welmer AK, Holmquist LW, Sommerfeld DK. Limited fine hand use after stroke and its association with other disabilities. J Rehabil Med. 2008; 40(8):603–8. https://doi.org/10.2340/16501977-0218 PMID: 19020692
10. Blennerhassett JM, Matyas TA, Carey LM. Impaired discrimination of surface friction contributes to pinch grip deficit after stroke. Neurorehabil Neural Repair. 2007; 21(3):263–72. https://doi.org/10.1177/1545968306295560 PMID: 17351081
11. Lin SL. Motor function and joint position sense in relation to gait performance in chronic stroke patients. Arch Phys Med Rehabil. 2005; 86(2):197–203. https://doi.org/10.1016/j.apmr.2004.05.009 PMID: 15706543
12. Hsu AL, Tang PF, Jan MH. Analysis of impairments influencing gait velocity and asymmetry of hemiplegic patients after mild to moderate stroke. Arch Phys Med Rehabil. 2003; 84(8):1185–93. https://doi.org/10.1016/s0003-9993(03)0030-3 PMID: 12917858
13. Niam S, Cheung W, Sullivan PE, Kent S, Gu X. Balance and physical impairments after stroke. Arch Phys Med Rehabil. 1999; 80(10):1227–33. https://doi.org/10.1016/s0003-9993(99)90020-5 PMID: 10527078
14. Poitawski L, Allison R, Briscoe S, Freeman J, Kilbride C, Neal D, et al. Assessing the impact of upper limb disability following stroke: a qualitative enquiry using internet-based personal accounts of stroke survivors. Disabil Rehabil. 2018; 40(10):945–51. https://doi.org/10.3109/09638288.2015.1068383 PMID: 26200448
15. Kessner SS, Schlemm E, Cheng B, Bingel U, Fiehler J, Gerloff C, et al. Somatosensory deficits after ischemic stroke: time course and association with infarct location. Stroke. 2019; 50(5):1116–23. https://doi.org/10.1161/STROKEAHA.118.023750 PMID: 30943883
16. Winward CE, Halligan PW, Wade DT. Current practice and clinical relevance of somatosensory assessment after stroke. Clin Rehabil. 1999; 13(1):48–55. https://doi.org/10.1177/026921559901300107 PMID: 10327097
17. Kalra L. Stroke rehabilitation 2009: old chestnuts and new insights. Stroke. 2010; 41(2):e88–90. https://doi.org/10.1161/STROKEAHA.109.572297 PMID: 20075345
18. Zandvliet SB, Kwakkel G, Nijland RHM, van Wegen EEH, Meskers CGM. Is Recovery of Somatosensory Impairment Conditional for Upper-Limb Motor Recovery Early After Stroke? Neurorehabil Neural Repair. 2020; 34(5):403–16. https://doi.org/10.1177/1545968320907075 PMID: 32391744
19. Rand D, Gottlieb D, Weiss PL. Recovery of patients with a combined motor and proprioception deficit during the first six weeks of post stroke rehabilitation. Physical & Occupational Therapy In Geriatrics. 2001; 18(3):69–87.
20. Pumpa LU, Cahill LS, Carey LM. Somatosensory assessment and treatment after stroke: An evidence-practice gap. Aust Occup Ther J. 2015; 62(2):93–104. https://doi.org/10.1111/1440-1630.12170 PMID: 25615889
21. Doyle S, Bennett S, Gustafsson L. Occupational Therapy for Upper Limb Post-Stroke Sensory Impairments: A Survey. British Journal of Occupational Therapy. 2013; 76(10):434–42.
22. Stein J. Robotics in rehabilitation: technology as destiny. Am J Phys Med Rehabil. 2012; 91(11 Suppl 3):S199–203. https://doi.org/10.1097/PHM.0b013e31826bcbbd PMID: 23080036
23. Chua KSG, Kua CWK. Innovating With Rehabilitation Technology in the Real World: Promises, Potentials, and Perspectives. Am J Phys Med Rehabil. 2017; 96(10 Suppl 1):S150–s6. https://doi.org/10.1097/PHM.0000000000000799 PMID: 28708632
24. Weinstein C, Requejo P. Innovative Technologies for Rehabilitation and Health Promotion: What Is the Evidence? Physical Therapy. 2015; 95(3):294–8. https://doi.org/10.2522/ptj.2015.95.2.294 PMID: 25734191
25. Keeling AB, Piitz M, Semrau JA, Hill MD, Scott SH, Dukelew SP. Robot enhanced stroke therapy optimizes rehabilitation (RESTORE): a pilot study. J Neuroeng Rehabil. 2021; 18(1):10. https://doi.org/10.1186/s12984-021-00804-8 PMID: 33478563
26. Zimmerli L, Krewer C, Gassert R, Müller F, Riener R, Lünenburger L. Validation of a mechanism to balance exercise difficulty in robot-assisted upper-extremity rehabilitation after stroke. J Neuroeng Rehabil. 2012; 9:6. https://doi.org/10.1186/1743-0003-9-6 PMID: 22304989
27. Dundar U, Toktas H, Solak O, Ulasli AM, Ergulu S. A comparative study of conventional physiotherapy versus robotic training combined with physiotherapy in patients with stroke. Top Stroke Rehabil. 2014; 21(6):453–61. https://doi.org/10.1310/tsr2106-453 PMID: 25467393
28. Schmidt H, Werner C, Bernhardt R, Hesse S, Krüger J. Gait rehabilitation machines based on programable footplates. Journal of neuroengineering and rehabilitation. 2007; 4(1):1–7. https://doi.org/10.1186/1743-0003-4-2 PMID: 17291335

29. Maceira-Elvira P, Popa T, Schmid A-C, Hummel FC. Wearable technology in stroke rehabilitation: towards improved diagnosis and treatment of upper-limb motor impairment. Journal of NeuroEngineering and Rehabilitation. 2019; 16(1):142. https://doi.org/10.1186/s12984-019-0612-y PMID: 31744553

30. Pollock A, Farmer SE, Brady MC, Langhorne P, Mead GE, Mehrholz J, et al. Interventions for improving upper limb function after stroke. Cochrane Database Syst Rev. 2014; 2014(11):Cd010820. https://doi.org/10.1002/14651858.CD010820.pub2 PMID: 25387001

31. Da Gama A, Fallavollita P, Teichrieb V, Navab N. Motor rehabilitation using Kinect: a systematic review. Games for health journal. 2015; 4(2):123–35. https://doi.org/10.1089/g4h.2014.0047 PMID: 26181806

32. Pugliese M, Ramsay T, Johnson D, Dowlatshahi D. Mobile tablet-based therapies following stroke: A systematic scoping review of administrative methods and patient experiences. PLoS One. 2018; 13(1): e0191566. https://doi.org/10.1371/journal.pone.0191566 PMID: 29360872

33. Kubis N. Non-Invasive Brain Stimulation to Enhance Post-Stroke Recovery. Front Neural Circuits. 2016; 10:56. https://doi.org/10.3389/fncir.2016.00056 PMID: 27512367

34. Dukelow SP, Herter TM, Moore KD, Demers MJ, Glasgow JI, Bagg SD, et al. Quantitative assessment of limb position sense following stroke. Neurorehabil Neural Repair. 2010; 24(2):178–87. https://doi.org/10.1177/1545968309345267 PMID: 19794134

35. Harrison JK, McArthur KS, Quinn TJ. Assessment scales in stroke: clinimetric and clinical considerations. Clin Interv Aging. 2013; 8:201–11. https://doi.org/10.2147/CIA.S32405 PMID: 23440256

36. Bishop L, Kitago T. Getting Involved in Research With Stroke Rehabilitation Technologies. Stroke. 2019; 50(2):e28–e30. https://doi.org/10.1161/STROKEAHA.118.023874 PMID: 30661500

37. Langan J, Subryan H, Nwogu I, Cavuoto L. Reported use of technology in stroke rehabilitation by physical and occupational therapists. Disabil Rehabil Assist Technol. 2018; 13(7):641–7. https://doi.org/10.1080/17483107.2017.1362043 PMID: 28812386

38. Eysenbach G. Improving the quality of Web surveys: the Checklist for Reporting Results of Internet Surveys (CHERRIES). J Med Internet Res. 2004; 6(3):e34. https://doi.org/10.2196/jmir.6.3.e34 PMID: 15471760

39. Bolognini N, Russo C, Edwards DJ. The sensory side of post-stroke motor rehabilitation. Restor Neurol Neurosci. 2016; 34(4):571–86. https://doi.org/10.3398/RNN-150606 PMID: 27080070

40. Langhorne P, Bernhardt J, Kwakkel G. Stroke rehabilitation. Lancet. 2011; 377(9778):1693–702. https://doi.org/10.1016/S0140-6736(11)60325-5 PMID: 21350049

41. Carey L, Macdonell R, Matyas TA. SENSe: Study of the Effectiveness of Neurorehabilitation on Sensation: a randomized controlled trial. Neurorehabil Neural Repair. 2011; 25(4):304–13. https://doi.org/10.1177/1545968310397705 PMID: 21350049

42. Fleming MK, Sorinola IO, Roberts-Lewis SF, Wolfe CD, Wellwood I, Newham DJ. The effect of combined somatosensory stimulation and task-specific training on upper limb function in chronic stroke: a double-blind randomized controlled trial. Neurorehabil Neural Repair. 2015; 29(2):143–52. https://doi.org/10.1177/1545968314533613 PMID: 24803495

43. de Diego C, Puig S, Navarro X. A sensorimotor stimulation program for rehabilitation of chronic stroke patients. Restor Neurol Neurosci. 2013; 31(4):361–71. https://doi.org/10.3233/RNN-120250 PMID: 23524843

44. De Bruyn N, Saenens L, Thijs L, Van Gils A, Ceulemans E, Essers B, et al. Sensorimotor stimulation for motor recovery in chronic stroke patients. Neural Engineering. 2019; 12(2):e0191566. https://doi.org/10.1371/journal.pone.0191566 PMID: 29284178
48. Saibach NM, Guilcher SJ, Jagial SB. Physical therapists’ perceptions and use of standardized assessments of walking ability post-stroke. J Rehabil Med. 2011; 43(6):543–9. https://doi.org/10.2340/16501977-0820 PMID: 21533335

49. Burton LJ, Tyson S, McGovern A. Staff perceptions of using outcome measures in stroke rehabilitation. Disabil Rehabil. 2013; 35(10):828–34. https://doi.org/10.3109/09638288.2012.709305 PMID: 22900574

50. Maribo T, Nielsen JF, Nielsen CV. Wide variation in function level assessment after stroke in Denmark. Dan Med J. 2018; 65(10). PMID: 30269746

51. Agyenkwa SK, Yarfi C, Banson AN, Kofie-Bediako WA, Abonie US, Angmorter SK, et al. Assessing the Use of Standardized Outcome Measures for Stroke Rehabilitation among Physiotherapists in Ghana. Stroke Research and Treatment. 2020; 2020:9259017. https://doi.org/10.1155/2020/9259017 PMID: 32665830

52. Gladstone DJ, Danells CJ, Black SE. The fugh-meyer assessment of motor recovery after stroke: a critical review of its measurement properties. Neurorehabil Neural Repair. 2002; 16(3):232–40. https://doi.org/10.1177/154596802401105171 PMID: 12234086

53. Sullivan KJ, Tilson JK, Cen SY, Rose DK, Hershberg J, Correa A, et al. Fugl-Meyer Assessment of Sensorimotor Function After Stroke. Stroke. 2011; 42(2):427–32. https://doi.org/10.1161/STROKEAHA.110.592766 PMID: 21164120

54. Connell LA, Tyson SF. Measures of sensation in neurological conditions: a systematic review. Clinical Rehabilitation. 2011; 26(1):68–80. https://doi.org/10.1177/0269215511412982 PMID: 21971756

55. Wu CY, Chuang IC, Ma HI, Lin KC, Chen CL. Validity and Responsiveness of the Revised Nottingham Sensation Assessment for Outcome Evaluation in Stroke Rehabilitation. Am J Occup Ther. 2016; 70(2):700290041p1-8. https://doi.org/10.5014/ajot.2016.018390 PMID: 26943116

56. Lincoln NB, Jackson JM, Adams SA. Reliability and Revision of the Nottingham Sensory Assessment for Stroke Patients. Physiotherapy. 1998; 84(8):358–65.

57. Kiper P, Baba A, Agostini M, Turolla A. Proprioceptive Based Training for stroke recovery. Proposal of new treatment modality for rehabilitation of upper limb in neurological diseases. Archives of Physiother. 2011; 5(1):6. https://doi.org/10.1186/s40945-015-0007-8 PMID: 29340175

58. Gopaul U, van Vliet P, Callister R, Nilsson M, Carey L. COMbined Physical and somatoSENSory training after stroke: Development and description of a novel intervention to improve upper limb function. Physiother Res Int. 2019; 24(1):e1748. https://doi.org/10.1002/pri.1748 PMID: 30230136

59. De Santis D, Zenzeri J, Casadio M, Masia L, Riva A, Morasso P, et al. Robot-assisted training of the kinesthetic sense: enhancing proprioception after stroke. Front Hum Neurosci. 2014; 8:1037. https://doi.org/10.3389/fnhum.2014.00389 PMID: 25601833

60. Sidarta A, Lim YC, Kuah CWK, Loh YJ, Ang WT. Robotic-based ACTive somatoSENSory (Act.Sens) retraining on upper limb functions with chronic stroke survivors: study protocol for a pilot randomised controlled trial. Pilot and Feasibility Studies. 2021; 7(1):207. https://doi.org/10.1186/s40814-021-00948-3 PMID: 34782024

61. Yeh IL, Holst-Wolff J, Elangovan N, Cuppone AV, Lakshminarayan K, Capello L, et al. Effects of a robot-aided somatosensory training on proprioception and motor function in stroke survivors. Journal of NeuroEngineering and Rehabilitation. 2021; 18(1):77. https://doi.org/10.1186/s12984-021-00871-x PMID: 33971912

62. Cappello L, Elangovan N, Contu S, Khosravani S, Konczak J, Masia L. Robot-assisted assessment of wrist proprioception. Front Hum Neurosci. 2015; 9:198. https://doi.org/10.3389/fnhum.2015.00198 PMID: 25926785

63. Zbytniewska M, Kanzler CM, Jordan L, Salzmann C, Liepert J, Lambery O, et al. Reliable and valid robot-assisted assessments of hand proprioceptive, motor and sensorimotor impairments after stroke. Journal of NeuroEngineering and Rehabilitation. 2021; 18(1):115. https://doi.org/10.1186/s12984-021-00904-5 PMID: 34271954

64. Li L, Tyson S, Weightman A. Professionals’ Views and Experiences of Using Rehabilitation Robotics With Stroke Survivors: A Mixed Methods Survey. Frontiers in Medical Technology. 2021; 3. https://doi.org/10.3389/fmedt.2021.780030 PMID: 35047969

65. Pinto D, Garnier M, Barbas J, Chang S-H, Charlifue S, Field-Fote E, et al. Budget impact analysis of robotic exoskeleton use for locomotor training following spinal cord injury in four SCI Model Systems. Journal of NeuroEngineering and Rehabilitation. 2020; 17(1):4. https://doi.org/10.1186/s12984-019-0639-6 PMID: 31924224

66. Wagner TH, Lo AC, Peduzzi P, Bravata DM, Huang GD, Krebs HJ, et al. An economic analysis of robot-assisted therapy for long-term upper-limb impairment after stroke. Stroke. 2011; 42(9):2630–2. https://doi.org/10.1161/STROKEAHA.110.606442 PMID: 21757677