

A Novel Tool for Quantitative Assessment of Lower Limb Proprioception: Demonstration with Young Adults, Elderly and Stroke Survivors

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**A Novel Tool for Quantitative Assessment of Lower Limb
Proprioception: Demonstration with Young Adults, Elderly and
Stroke Survivors**

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Abstract

Background

Stroke and ageing are common causes for proprioceptive impairments. Such impairments may contribute to disabilities in daily living activities, such as walking. Yet, current rehabilitation methods mainly focus on motor disabilities, and often neglect somatosensory impairments. Moreover, clinical methods for proprioception assessment of both the upper and lower limb are subjective and suffer from inconsistency between evaluators, and the majority of the research in quantitative assessment of proprioception focuses on the upper limb. To address these gaps, we present a novel tool for quantitative assessment of proprioception of the lower limb.

Methods

We developed a tool that consists of a magnetic tracking system with magnetic sensors placed on the participants' toes while the participants were laying on their side. We designed an assessment protocol that includes contralateral position matching tests and ipsilateral position matching tests, and applied them to both lower limbs (N: non-dominant and D: dominant). We validated the tool on three groups of participants: young adults (n=18), elderly (n=8), and stroke survivors (n=5) by comparing the results of the mean absolute error (MAE), bias and the mean variable error (MVE).

Results

We evaluated the effect of group type, proprioceptive input, task type and their interactions. We compared between young adults and elderly with statistical analysis, and demonstrated the results of the stroke survivors. We found significant differences in MAE and bias between the elderly and young adults in the contralateral tasks, particularly once spatial information is transmitted from the N limb to the D limb, indicating that the ability to transit spatial information contralaterally

becomes more challenging with age. The bias also indicated that the contralateral task is more challenging with the groups, independently.

Conclusions

Using contralateral position matching may be an effective way to identify potential somatosensory impairments. In order to avoid a long and unnecessary assessment, we suggested using contralateral position matching as a screening phase in identifying lower limb proprioceptive impairments, followed by ipsilateral position matching only for individuals with impaired results for identifying possible confounds from motor and cognitive impairments.

Key words

Proprioception, lower-limb, young adults, elderly, stroke survivors, position matching, contralateral position matching, ipsilateral position matching, impairment, aging, memory, transfer between hemispheres.

Background

Stroke is a common cause of impairments in everyday functions. Stroke commonly causes motor, somatosensory and cognitive impairments, depending on the severity of the damage and its location (Connell, Lincoln and Radford, 2008),(Sturm *et al.*, 2002). Only 28-35% of stroke survivors indicate being fully recovered three months after stroke, while only 30-38% of stroke survivors report full recovery twelve months after stroke (Sturm *et al.*, 2002), and many stroke survivors develop disorders in the domains of mobility, everyday activities, physical independence (Sturm *et al.*, 2002),(Lai *et al.*, 2002) and irregular gait patterns (Balaban and Tok, 2014). Some

of these disorders may be attributed to somatosensory deficits (Tyson *et al.*, 2013), but these deficits are often neglected in rehabilitation (Kalra, 2010).

Another case for diminishing somatosensory function is the ageing process (Shaffer and Harrison, 2007). With age, the dynamic response of muscle spindles and the atrophy of axons may be decreased, which would lead to distorted processing of sensory input (Ferlinc *et al.*, 2019). As a result, some elderly develop somatosensory impairments that diminish the sense of balance, and increase the risk of falling (Shaffer and Harrison, 2007),(Goble *et al.*, 2009).

Somatosensory deficits may include impairment in tactile sensation, proprioception, or both. Proprioception arrives from the joints, muscles and tendons and informs us where our limbs are located (Hillier, Immink and Thewlis, 2015),(Han *et al.*, 2016). In contrast, tactile sensation, which is out of the scope of this paper, arrives from mechanoreceptors in the skin. More than half of stroke survivors suffer from proprioceptive disorders (Tyson *et al.*, 2013). Proprioception plays an important role in gait. The sense of lower-limb movement and positioning enables gait, by providing the necessary feedback for lifting and swinging the limbs in the air, as well as placing them accurately on the ground so that the step sequence would be synchronized and symmetrical. For example, information from hip joints and load receptors from the feet is necessary for activation of lower-limb muscles to initiate walking (Dietz, 2002),(Dietz and Duysens, 2000). Hence, understanding lower limb proprioception is necessary to improve treatment and rehabilitation methods in cases of impaired gait.

Nevertheless, research of proprioception impairments is limited, and it is difficult to characterise the extent of these impairments due to the large variability among stroke survivors: they vary in age, gender, modalities, the severity of damage and other factors (Connell, Lincoln and Radford, 2008). An important limiting factor in the research of proprioceptive impairments is

the lack of objective and quantitative tools (Hillier, Immink and Thewlis, 2015),(Sayar and nüböl, 2017). This is partially due to the perception among therapists that motor based assessments provide sufficient information about somatosensory function. Yet, clinicians also indicate that somatosensory evaluation is important for selecting the proper rehabilitation plan for the patient and the severity of stroke (Winward, Halligan and Wade, 1999).

When proprioception is assessed, therapists rely mainly on observation or on tests that assess the ability to detect static position or motion (Hillier, Immink and Thewlis, 2015). The Rivermead Assessment of Somatosensory Performance (RASP), includes a joint movement test for the assessment of proprioception. In this test passive movements are applied on a particular joint and the patient is asked to indicate if a movement was applied and then indicate its direction (Winward, Halligan and Wade, 2002). The Erasmus MC Nottingham Sensory Assessment (EmNSA) also includes an assessment of the ability to recognize the direction of a passive movement administered by the therapist (Stolk-Hornsveld *et al.*, 2006). Both assessments are conducted on both the upper and lower limbs' joints. In another common test, the Fugl-Meyer, the examiner makes small alterations in the position of a joint (either of the upper or the lower limb), and the participant is required to indicate this alteration verbally or by matching the joint position with the contralateral unaffected limb (Fugl-Meyer *et al.*, 1975). However, this test is limited if the patient suffers from aphasia, hemispatial inattention, and other cognitive impairments (Gladstone, Danells and Black, 2002). Additional clinical assessments include joint specific assessments. For example: thumb finding test and the finger nose test, where the upper limb is moved by the examiner and then the participant is asked to match their position (thumbs) to each other or in front of their nose. The distal proprioception test is applied to the big toe, where the examiner grasps it and performs vertical movements (up and down) while the participant observes it, and then is asked to repeat

the movement with closed eyes (Sayar and nüböl, 2017). These types of evaluation raise the question of objectivity and quantification, since the severity of the impairment may be interpreted differently by different physical therapists because it is harder to quantify it by simply observing it (Hillier, Immink and Thewlis, 2015),(Sayar and nüböl, 2017),(Han *et al.*, 2016).

To address the limitations of the clinical assessment methods, quantitative, robotic and sensorized methods of proprioception assessment were developed and studied in healthy and impaired individuals. These include threshold to detection of passive movement (TTDPM), active movement extent discrimination assessment (AMEDA) and joint position reproduction (JPR) (Han *et al.*, 2016). Such assessments and their variations may be conducted in a contralateral setup, by mimicking the movement with the opposite limb or in an ipsilateral setup, where the movement is repeated from memory. In the upper limb, proprioception assessment was commonly studied by using exoskeletons that are attached to the arms, forearms and fingers of the participants. The participants were asked to match the position of a target limb in space (Leibowitz *et al.*, 2008), to mirror the position of a finger (Dukelow *et al.*, 2010), to mirror the joint angle of the elbow (Gurari *et al.*, 2018), to adjust elbow joint angle to a given angle with and without vision (Sketch, Bastian and Okamura, 2018) etc. The use of robotic setups enables passive movement and a direct evaluation of proprioception, but requires elaborate, big, and expensive robotic devices.

For the specific assessment of lower limb proprioception, many studies suggested examining particular joints of the lower limb, such as the knee (Galamb *et al.*, 2018),(Study, Nitsure and Prabhu, 2017) and the ankle (Yasuda *et al.*, 2014),(Forestier, Teasdale and Nougier, 2002),(Iandolo *et al.*, 2018),(Boisgontier and Nougier, 2013a),(Boisgontier and Nougier, 2013b),(Boisgontier and Nougier, 2013a),(Boisgontier *et al.*, 2012) and examine errors in the orientation of the joint while conducting contralateral and ipsilateral matching. Ofek et al. (Ofek,

2019), examined ipsilateral position matching of the non-dominant and dominant limbs of young adults and elderly, by measuring the distance error between a target and the position of the foot on a piece of paper. Very few studies examined the proprioceptive sense of an end point of a limb like (Ofek, 2019), despite that end point placement of a limb in the environment is considered more ecological and realistic (Han *et al.*, 2016).

In this work, we developed a novel tool for proprioception assessment of the end point of the lower limb, based on contralateral and ipsilateral position matching tasks, using magnetic trackers that allowed tracking the position of the limb, similarly to (Leibowitz *et al.*, 2008). It allowed us to quantify the deviations of the matching automatically without the need for a robotic setup, and can be administered in any room as long as the proper distance from ferromagnetic materials is kept. We first present the proposed assessment method and protocol in the Methods section. In the Results section, we present statistical comparison between the young adults and elderly, and only a demonstration of the assessment for the stroke survivors due to the small sample size of this group. We also present several examples of detailed analysis of the assessment for individual participants in the Case Studies section. Here, we demonstrate the process of possible pinpointing of the source of the impairment. We conclude the paper with a Discussion highlighting implications, limitations, and future work.

Methods

Participants

31 participants took part in the study: 18 young adults, 8 elderly, and 5 stroke survivors. All the participants were over 18 years old. The young adults were recruited from the community of students of Ben-Gurion University of the Negev. Elderly participants were recruited from the communities of southern Israel. None of the young adults or elderly experienced a stroke, a severe

brain injury, or any other neurological impairment. Stroke survivors were recruited from local communities and from Adi-Negev Nehalat Eran rehabilitation centre, Ofakim, Israel. The assessment of young adults and elderly took place in Ben-Gurion University of the Negev in Beer-Sheva, Israel, and the assessment of stroke survivors took place at Adi Negev and Ben-Gurion University of the Negev, Beer-Sheva. All stroke survivors were interviewed before the assessment, to ensure that they could walk (with or without the assistance of a cane or walker) and the affected body side was determined. Additionally, all the participants filled in a questionnaire about their age, physical activities in the past and the present, medication use, and previous injuries or known sensory deficits. One of the elderly had metal particles in their leg, but in calibration, inner body metals did not affect the calibration.

Before the assessment, the lower body length (from the pelvic bone to the ankle bone), height, and weight of each participant were measured. To identify the dominance of the lower-limb, the participants were asked to kick a ball, and the kicking limb was defined as the dominant limb (van Melick et al., 2017). A summary of the participants' demographics is presented in table 1.

Table 1 Demographics

Group type	Participants	Age	Lower limb dominance	Lower limb impairment
Young adults	male: 9, female: 9	25.33±2.25	right: 15, left:3	-
Elderly	male: 3, female: 5	71.75±4.53	right: 8	-
Stroke survivors	male: 3, female: 2	64.40±7.09	-	right: 3, left: 2

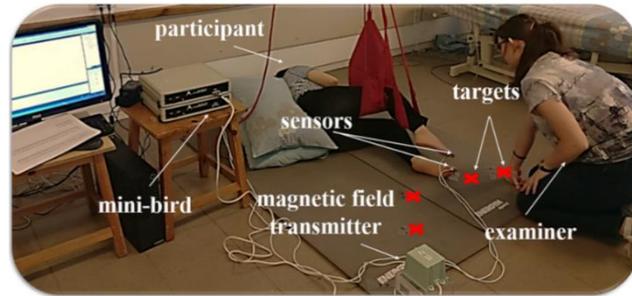


Figure 1 Experimental setup. The participant lays on the mattress with one limb held by a sling, while the toe of the other limb is on a target (the targets are marked in red) and the examiner sits near the participant and moves their limbs. The magnetic sensors are attached to the toes of the participant and are linked to the mini-bird devices, as well as the magnetic field transmitter.

Experimental setup

We developed a novel approach for proprioceptive assessment of the lower limbs using magnetic tracking, similar to the approach that was successfully used and validated against clinical metrics for assessment of upper limb proprioception in (Leibowitz et al., 2008). We used two mini-bird devices (Ascension Technologies, VT, USA) with a six-dimensional magnetic position sensor attached to each of them. The sensors' position coordinates were recorded relative to the position of the magnetic field transmitter. To minimize magnetic interferences, any equipment with ferromagnetic components was moved away from the assessment area. A mattress was placed beneath a sling setup as in Fig. 1.

We used four target positions at two different angles relative to the centreline of the body and two different distances (Fig. 2A-B). The angles were 30° in front of the centreline of the mattress and 10° behind it. The distances were adjusted to the body size of each participant to provide a feasible and comfortable workspace: two targets were placed at 60% of the measured lower body length of the participant and two targets at 80%. The placement was symmetrical as in Fig. 2.A-B for both sides of the body. The system was calibrated at the beginning of every evaluation day, before the evaluation of the first participant. The calibration process included finding the distance between four different positions (usually the position of four targets of the previous participant). The distances were calculated, repeated ten times, and then averaged. The calibration error was set at 10mm since the size of each position-sensor was 5mm, so this value is defined as the minimal effect size discussed throughout the paper. The calibration process was then repeated by evaluating the vertical distance between the sensors, while one sensor is placed above the other.

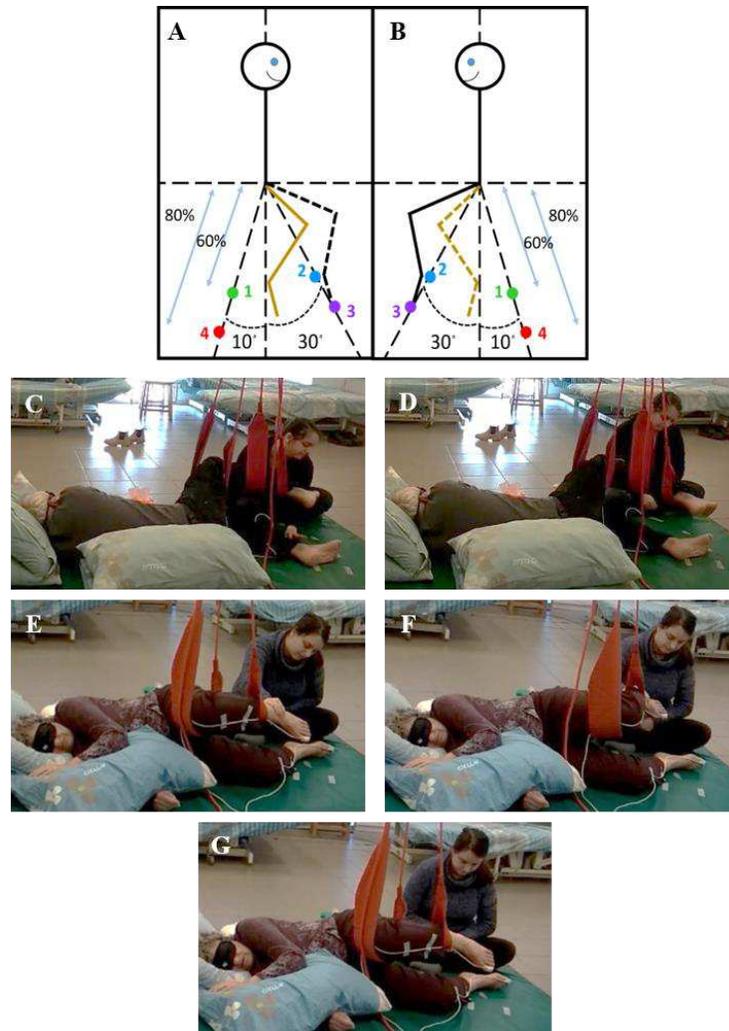


Figure 2 Setup illustration. (A-B), contralateral matching (C-D) and ipsilateral matching tasks (E-G). A-B) Targets setup for both sides of the body, where the participant is laying on the side and one limb is placed on a mattress (black) and the other limb (brown) is held by a sling. The dashed limb represents the left limb, while the continuous limb represents the right. C) Contralateral position matching: The examiner places the toe of the participant on a target. D) The participant places the test toe above the position of the target toe. E) Ipsilateral position matching: The examiner places the target toe above a target and the participant is memorizing its position. F) The examiner moves the limb away. G) The participant moves the toe to the memorized target position.

Assessment protocols

Participants were asked to lay on their side on the mattress with the adjusted targets. One limb was held by a sling and the other limb was placed on the mattress (Fig. 2.C-G). The magnetic tracking sensors were placed on the toes of the participants. The assessment was based on two tasks: contralateral position-matching and ipsilateral position-matching, that were repeated for both the dominant (*D*) and the non-dominant (*N*) limbs for the young adults and the elderly, and the unaffected (*U*) and affected (*A*) limbs of the stroke survivors, respectively. The evaluation of each condition included overall forty trials, ten trials per target. In all these tests, the examiner placed the toe of the target limb on one of the targets and asked the participant to place the toe of the test limb above the same target. In the remainder of the paper, we refer to the tests with a two-letter coding in which the first letter designates the target limb, and the second the test limb.

1) Contralateral position-matching (N/A, or D / U)

The examiner placed the toe of the bottom limb (target) on a target on the mattress (Fig. 2.C). Then, the examiner asked the participant to place the toe of the upper limb (test) above the target toe, to match their positions (Fig. 2. D). In this task, the participants had to sense the position of the target using the proprioception of the target limb, transmit the position from the target limb to the test limb, and execute the matching with the test limb. For the young adults and the elderly, we coded the condition in which the non-dominant (*N*) limb was the target and the dominant (*D*) limb was the test as ND and DN for the opposite. Similarly, for the stroke survivors, the condition in which the affected (*A*) limb was the target and the unaffected (*U*) limb was the test as AU and UA for the opposite.

2) Ipsilateral position-matching (NN/AA, DD/UU)

The bottom limb was not used, so the upper lower limb is both the target and the test limb. The examiner placed the toe of the test limb above the target and asks the participant to memorize its position (Fig. 2. E). Then, the limb is moved away (to the position of the previous target) (Fig. 2. F). If the participants did not memorize the position properly and asked to repeat the memorization, the process was repeated. Then, the participants were asked to move the toe of the same limb (test limb) to the memorized target position (Fig. 2. G). In this task, the participants had to sense the target position using the proprioception of the test limb, memorize its position and perform the matching using the test limb (same limb). We marked the condition in which the non-dominant/affected limb was used as NN/AA and DD/UU for the dominant/non-affected limb.

Excluded and adjusted trials

Two of the elderly did not perform the conditions DN and NN because we initially planned on examining the conditions ND and DD in elderly and stroke survivors to avoid potential motor impairments of the N/A limb. One stroke survivor did not perform the conditions DN and NN, and could only partly perform the condition DD. Position signals that were distorted due to uncontrolled movement of the participants were either adjusted or excluded from the analysis. The excluded and adjusted trials were trials that were suspected to be inconsistent by the examiners, so they were examined and changed after the fact, if necessary. The adjusted trials were shortened by omitting the beginning, end, or both of the signals, so mainly the stable values of the position signal remained. Among the young adults, 0.49% of the trials were excluded, among the elderly 3.88% and 5.14% among the stroke survivors. The maximum number of trials that were excluded per condition among the participants was three, except in the following cases: one elderly participant was not able to reach target 2 due to pain and discomfort in the limbs, so target 2 was

skipped in their evaluation. One stroke survivor could not complete one of the conditions that were examined, and the last 11 trials of another condition were not considered in their analysis due to fatigue. In the evaluation of another stroke survivor, 21 trials were excluded due to magnetic disturbance. Moreover, among the young adults, 0.63% of the collected data was adjusted by shortening the signals, 0.8% among the elderly, and 2.77% among the stroke survivors.

Interpretation of comparisons between the conditions

We divided the possible comparisons between the different conditions into six sets of paired comparisons, and in each of these paired comparisons, the conditions had one characteristic in common (Fig. 3). For example, when comparing the ND and NN conditions, the target is sensed with the same limb (N), and thus, the proprioceptive input is identical. But, the NN condition required the participants to memorize the target position and use the N limb to execute the test, whereas the ND required them to transmit the position from N to D, and use the D limb to execute the task. Hence, both the cognitive and the motor tasks are different. Fig. 3 presents similar reasoning for all the six paired comparisons. Table 2 describes the impairments that can be detected if the marked conditions (V) are impaired. We present an example of such assessment in the case series section. Note that not in all cases of multiple impairments it is possible to isolate a specific source of impairment. For example: if conditions NN, DD and ND produce impaired results, the source of the impairment might be motor (in the dominant limb) and proprioceptive (in the non-dominant limb), or it could be a combination of a motor impairment (in the dominant limb) and a cognitive-memory impairment.

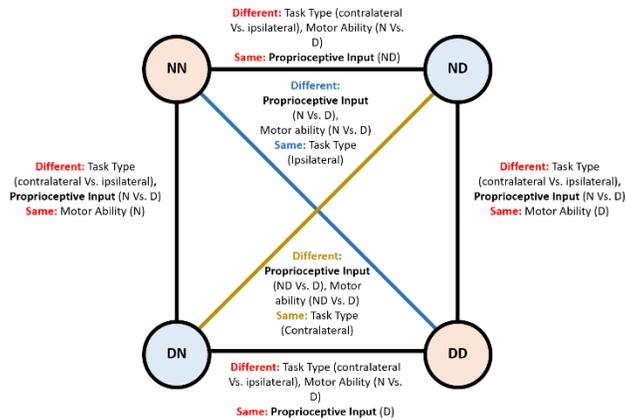


Figure 3 Experimental conditions and what can be learned from comparisons between them. The descriptions outside the square explain the differences and similarities between every two conditions on the perimeter, and the descriptions inside the square explain the differences and similarities between the conditions across the diagonals (blue for NN Vs. DD and yellow for DN Vs. ND).

Table 2 Identifying motor, proprioceptive and cognitive impairments from the condition comparisons

	Impairment	Limb/Type	Condition (V-for impaired result)			
			NN	DD	ND	DN
Single impairment	Motor	N	V	-	-	V
		D	-	V	V	-
	Proprioceptive	N	V	-	V	-
		D	-	V	-	V
	Cognitive	Memory	V	V	-	-
		Transferring between hemispheres	-	-	V	V
Two impairments	proprioceptive (N) + motor (N)		V	-	V	V
	proprioceptive (N) + motor (D)		V	V	V	-
	proprioceptive (D) + motor (N)		V	V	-	V
	proprioceptive (D) + motor (D)		-	V	V	V
	proprioceptive (N) + memory		V	V	V	-
	proprioceptive (N) + transferring between both legs		V	-	V	V
	proprioceptive (D) + memory		V	V	-	V
	proprioceptive (D) + transferring between both legs		-	V	V	V
	motor (N) + memory		V	V	-	V
	motor (N) + transferring between both legs		V	-	V	V
	motor (D) + memory		V	V	V	-
	motor (D) + transferring between both legs		-	V	V	V
Three impairments and more			V	V	V	V

Data Analysis

Data acquisition was performed with a custom written C++ code. In all the tasks, the position of the target and the matching were recorded for several seconds and then the mean of the recording was used for the analysis. We evaluated the performance of every participant in every target in all the conditions that were performed. Since the examiners moved the target limb in every trial, the positions of a certain target were not always identical, as can be seen in Fig. 4, where the targets' position of a particular trial were presented with “o” symbol, and had both bias and variability. Hence, we made sure that our metrics account for these bias and variability, and quantify the added bias or added variability due to the answers of the participants. For each target, we calculated with a custom-written Matlab (@ 1994-2019 The Mathworks, Inc.) code the “Mean Absolute Error” (MAE), “Bias”, “Mean Variable Error” (MVE) as follows:

1) Mean Absolute Error (MAE)

The magnitude of the planar distance between the target position and the position obtained by the test limb. The obtained values were averaged across the trials (up to ten trials per target) and across the four targets per participant in Fig. 5.A. MAE represents the mean deviation that the participant had during the matching. Because the MAE is affected by both the bias and the variance, and each of these sources of error has different implications on isolating the proprioceptive impairment, we also calculated separately the Bias and Mean Variable Error. This metric represents the absolute distance error, disregarding the direction of the error.

$$\text{MAE} = \frac{\sum_{i=1}^N \|x_{\text{match},i} - x_{\text{target},i}\|}{N}, \quad (1)$$

where N is the number of the trials, \bar{x} is the mean position in a 2-D plane, representing the mean x and mean y positions of the matching results and the targets and $\|\cdot\|$ represents the Euclidean distance.

2) Bias

The planar absolute distance between the mean target position and the mean test position. The mean positions were found by calculating the mean position of the target limb and test limb, respectively, by averaging the positions across the trials (up to ten trials per target). The bias represents the deviation of the center of the distribution of the answers executed by the test limb from the targets sensed by the target limb. Unlike MAE, bias regards the directions of the errors and averages them, so errors in opposite directions were neglected, while errors in similar directions are emphasized by bias.

$$\text{Bias} = \|\bar{x}_{target} - \bar{x}_{match}\|, \quad (2)$$

3) Mean Variable Error (MVE)

The distance between the mean position matching and all matching positions of the trials, relative to the distance between the mean target position and the target positions per each target. The MVE represents the relative scattering of the answers regardless of their center. The distances of the matching results from the mean matching position are averaged (the mean variable error of the matching results) relative to the same calculation with the targets' positions. An enlarged ratio would represent scattered results with matching errors in different directions.

$$\text{MVE} = \frac{\sum_{i=1}^N \|\bar{x}_{match} - x_{match,i}\|}{N} / \frac{\sum_{i=1}^N \|\bar{x}_{target} - x_{target,i}\|}{N}, \quad (3)$$

We evaluate this ratio on a logarithmic scale to create a normally distributed metric in the statistical analysis, yet the results of this metric in Fig. 5.C represent the actual ratio by transforming it back to its actual value using an exponential calculation. The logarithmic value used for the statistical analysis was:

$$\ln(\text{MVE}) = \ln\left(\frac{\sum_{i=1}^N \|\bar{x}_{match} - x_{match,i}\|}{N}\right) - \ln\left(\frac{\sum_{i=1}^N \|\bar{x}_{target} - x_{target,i}\|}{N}\right),$$

Statistical analysis

We performed statistical analysis to compare between the assessments of proprioception of the young adults and the elderly. For each metric, we fitted a 3-way ANOVA with repeated measures model. The fixed effects were the group type (young adults or elderly), the limb of proprioceptive input/target limb (D or ND) and the type of task (contralateral position matching or ipsilateral position matching). We also examined the interactions between group type, proprioceptive input, and task type (all possible combinations). The random effects were the participants and targets' numbers (as presented in Fig. 2.A-B), and the participants were nested within the group type. Planned comparisons were conducted with the effects and interactions that were found significant by two tailed t-tests of planned comparisons (between group types in all significant effects, between task type and within each group if was significant) of the regression coefficients of the ANOVA, with Bonferroni corrections. Significant effects were determined at the $p < 0.05$ threshold level.

This statistical comparison between the young adults and elderly serves for the purpose of demonstration of the novel assessment tool. Hence, we did not perform a power analysis and present the statistical inference as directions for future hypothesis-driven research. Moreover, the stroke survivors had individually unique impairments due to specific and individual damage. Therefore, we did not perform statistical analysis on their results at all, and we do not present even their summary statistics but rather show their individual data points in Fig. 5, and discuss two of them in the Case Studies section.

Results

In Fig. 4, examples of the individual data of a representative young adult and an elderly participant in each condition are presented, depicting the position of the recorded target and test limb of every trial and every target (distinguished by colour). The position of the target limb (represented by 'o') and the test limb ('x'), as well as the mean target position (triangle) and mean test position (diamond). Comparing these two visualizations already suggests that there is some impairment in the performance of the elderly participant. Such visualization of the results of each participant is the first output of our novel method for assessment of proprioception and can be visually examined by the clinician to support their qualitative assessment.

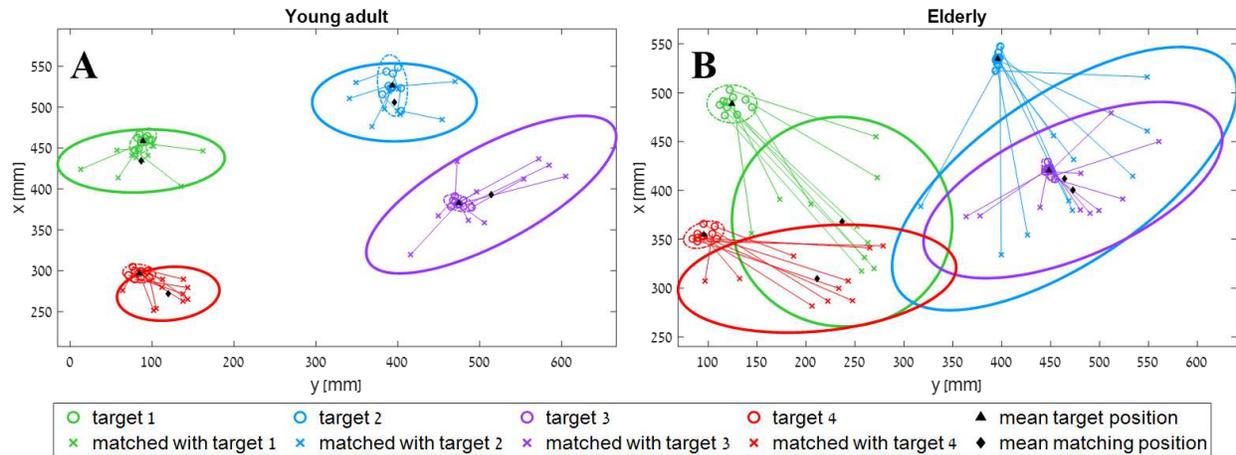


Figure 4 Individual results. A. Example of a representative young adult from the ND condition. B. Example of a representative elderly from the ND condition. The different colours represent the different targets, the “x” represents the matching position of target position “o” in a certain trial, and the line connecting them is the matching-deviation (absolute error) of the trial, the triangle is the mean target position and the diamond is the mean matching position of the test limb. The ellipse represents 95% confidence interval (Wang, Shi and Miao, 2015) (continuous for the matching positions and dashed for the target positions). Where the target ellipse is not visible it is because it is too small to be visible behind the individual data points.

The results of the statistical analysis of the young adults and elderly are summed up in tables 3 and 4. Any significant differences of the targets are not discussed, because the targets were chosen arbitrarily to span a large portion of the workspace of the toe of the leg. Fig. 5 presents the results of the three examined groups: young adults, elderly, and stroke survivors, and every participant is represented with a single dot, 'o', diamond, '◇', and triangle, 'Δ', respectively, depicting the mean value of the metric across repetitions and targets for the participant in the conditions that they participated in. First, examining the results in Fig. 5, we see that there was large variability among the elderly and stroke survivors compared to the young adults. The MAE, bias and MVE were all larger in the contralateral position matching compared to the ipsilateral position matching, for both the elderly and young adults (MAE: $F_{1,361}=37.38$, $\Delta=16.42\text{mm}$, bias: $F_{1,361}=73.62$, $\Delta=26.03\text{mm}$, MVE: $F_{1,361}=50.49$, $\Delta=1.34$ [ratio]) this suggests that overall the contralateral position matching is more difficult than the ipsilateral position matching regardless to the proprioceptive or motor abilities of the individuals. The rest of the contrasts differed between metrics.

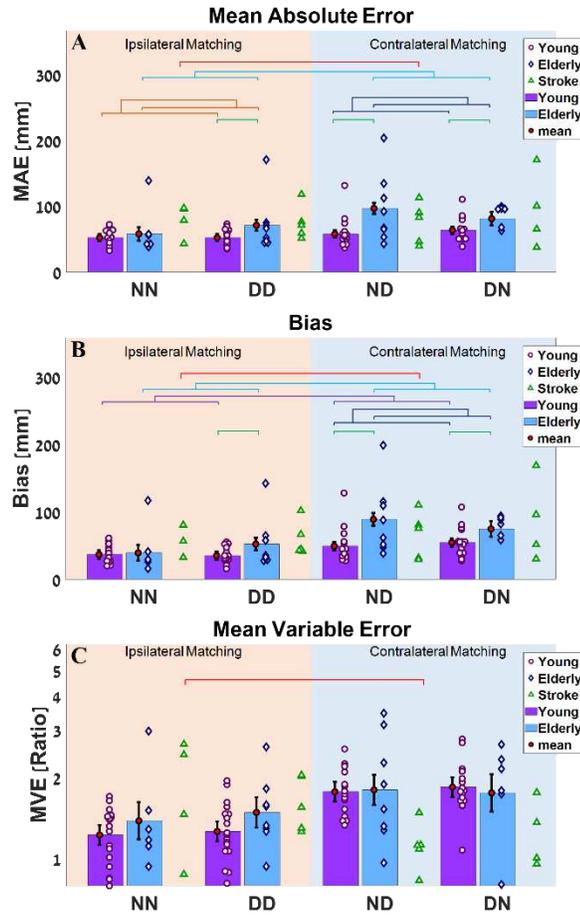


Figure 5 MAE, Bias, and MVE. The bars and symbols represent different groups: purple dots- young adults, blue diamonds- elderly, and green triangles- stroke survivors. The background represents the task type: pink- ipsilateral position matching and blue- contralateral position matching. The red dots represent the mean results of every group and every condition, and the black line represents 95% confidence interval for the estimated mean. Both the means and 95% are calculated based on the prediction of the linear model fitted to the data. The brackets represent the significant differences that were found in the planned comparisons: green- significant differences between the elderly and young adults in the condition; dark blue- significant difference between the elderly and young adults in the contralateral task; brown- significant difference between the elderly and young adults in the ipsilateral task; purple- significant difference between the contralateral and ipsilateral task in the young adults; light blue- significant difference between the contralateral and ipsilateral task in the elderly; red- significant difference between the task types. A) Mean absolute error (MAE), B) Bias, and C) Mean variable error (MVE). The results of MVE represent the actual ratio of formula (3) and not their logarithmic transformations that were used for the statistical analysis.

Mean absolute error

A significant difference ($\Delta=20.24\text{mm}$, $F_{1,24,91}=5.73$, $p=0.02$) was found between the elderly and young adults, where the elderly had the larger MAE. The interaction of group type and task type was significant ($F_{1,361}=8.89$, $p<0.05$). The MAE of the elderly group in the contralateral position matching tasks is significantly larger than the MAE of young adults ($\Delta=28.25\text{mm}$, $t_{361}=7.26$, $p<0.01$); the difference in ipsilateral position matching was significant as well ($\Delta=12.23\text{mm}$, $t_{361}=3.14$, $p<0.01$). Additionally, within group differences were noticed regarding task type. The elderly had a significant difference between the contralateral position matching and the ipsilateral position matching ($\Delta=24.43\text{mm}$, $t_{361}=5.32$, $p<0.01$). The young adults had a small difference in the range of the calibration error ($\Delta=8.41\text{mm}$, $t_{361}=3.02$, $p<0.01$). Moreover, the task type was significant as well ($\Delta=16.42\text{mm}$, $F_{1,361}=37.38$, $p<0.05$). Finally, the interaction of group type, task type and proprioceptive input was also statistically significant ($F_{1,361}=9.27$, $p<0.05$), indicating that the two groups had differences between them in the examined conditions. In the planned comparison test analysis, the only condition that did not produce a significant difference between both groups was NN ($t_{361}=0.96$, $p=0.34$). Significant differences were found among the young adults and the elderly in DD ($\Delta=18.77\text{mm}$, $t_{361}=3.70$, $p<0.01$), DN ($\Delta=17.56\text{mm}$, $t_{361}=2.97$, $p<0.01$) and the most pronounced difference was in ND ($\Delta=38.93\text{mm}$, $t_{361}=7.67$, $p<0.01$). Other results are presented in tables 3 and 4 and include the non-significant effects. By examining the MAE, the most pronounced difference between the elderly and young adults is found in the contralateral matching task, particularly in ND. The MAE gives us the sense of deviation that participants had across the assessment. Larger MAE values suggest consistently producing larger deviations from the target, as those are most apparent in the elderly.

Bias

Similar to MAE, a significant difference was found between both groups ($\Delta=19.8\text{mm}$, $F_{1,25.22}=5.74$, $p=0.02$) in the bias. The interactions of group type with task type ($F_{1,361}=10.96$, $p<0.05$) and group type, proprioceptive input and task type ($F_{1,361}=7.15$, $p=0.01$) were significant as well. The planned comparisons analysis revealed significant differences between the two groups in contralateral position matching tasks ($\Delta =29.85\text{mm}$, $t_{361}=6.79$, $p<0.01$), and in conditions DD ($\Delta =17.07\text{mm}$, $t_{361}=2.98$, $p<0.01$), DN ($\Delta =20.07\text{mm}$, $t_{361}=3.01$, $p<0.01$) and ND ($\Delta =39.62\text{mm}$, $t_{361}=6.91$, $p<0.01$). There were no significant differences between the groups in NN ($t_{361}=0.37$, $p=0.71$) and in ipsilateral position matching tasks ($t_{361}=2.22$, $p=0.03$). Within group analysis revealed significant differences between contralateral matching and ipsilateral matching in both groups, while the larger difference was noticed in the elderly group (young adults: $\Delta =15.98\text{mm}$, $t_{361}=5.09$, $p<0.01$, elderly: $\Delta =36.07\text{mm}$, $t_{361}=6.95$, $p<0.01$). Moreover, the bias was significantly larger in contralateral position matching tasks than in ipsilateral position tasks ($\Delta=26.03\text{mm}$, $F_{1,361}=73.62$, $p<0.05$). The bias emphasizes the difference in the test results of the elderly and the young adults. The elderly had greater bias values in the contralateral task, suggesting that this is the task that is more effective in discriminating the participants with a proprioceptive impairment from the participant with no proprioceptive impairment.

Mean variable error

The only effect that revealed a significant difference was the task type (ratio=1.34, $F_{1,361}=50.49$, $p<0.05$) which implies that MVE is larger in the contralateral position matching tasks than in ipsilateral position tasks. This indicates that the deterioration in proprioception, if happens with age, does not affect variability.

Table 3 statistical results of the main effects.

Effect	MAE		Bias		MVE	
Group type	F _{1,24.91}	5.73	F _{1,25.22}	5.74	F _{1,26.21}	0.54
	p	0.02	p	0.02	p	0.47
Participant (nested in group type)	F _{24,361}	10.59	F _{24,358}	7.87	F _{24,358}	4.40
	p	p<0.05	p	p<0.05	p	p<0.05
Proprioceptive input	F _{1,361}	0.09	F _{1,361}	0.04	F _{1,361}	0.48
	p	0.77	p	0.85	p	0.49
Task type	F _{1,361}	37.38	F _{1,361}	73.62	F _{1,361}	50.49
	p	p<0.05	p	p<0.05	p	p<0.05
Target	F _{3,361}	10.66	F _{3,361}	10.38	F _{3,361}	3.02
	p	p<0.05	p	p<0.05	p	0.03
Input & task type	F _{1,361}	4.17	F _{1,361}	2.52	F _{1,361}	0.26
	p	0.04	p	0.11	p	0.61
Group type & input	F _{1,361}	0.60	F _{1,361}	0.17	F _{1,361}	0.02
	p	0.44	p	0.68	p	0.89
Group type & task type	F _{1,361}	8.89	F _{1,361}	10.96	F _{1,361}	3.69
	p	p<0.05	p	p<0.05	p	0.06
Group type & input & task type	F _{1,361}	9.27	F _{1,361}	7.15	F _{1,361}	0.37
	p	p<0.05	p	0.01	p	0.54

Table 4 statistical results of the planned comparisons.

			Metric		
			MAE [mm]	Bias [mm]	MVE [ratio]
Main Effects	Group type (Elderly-young adults)	Δ	20.24	19.80	-
	Proprioceptive Input limb (D-N)	Δ	-	-	-
	Task type (Contralateral-ipsilateral)	Δ	16.42	26.03	1.34
Interactions	Contralateral: Elderly-young adults	t_{361}	7.26	6.79	-
		p	p<0.01	p<0.01	-
		Δ	28.25	29.85	-
	Ipsilateral: Elderly-young adults	t_{361}	3.14	2.22	-
		p	p<0.01	0.03	-
		Δ	12.23	9.76	-
	ND: Elderly-young adults	t_{361}	7.67	6.91	-
		p	p<0.01	p<0.01	-
		Δ	38.93	39.62	-
	DN: Elderly-young adults	t_{361}	2.97	3.01	-
		p	p<0.01	p<0.01	-
		Δ	17.56	20.07	-
	NN: Elderly-young adults	t_{361}	0.96	0.37	-
		p	0.34	0.71	-
		Δ	5.70	2.46	-
	DD: Elderly-young adults	t_{361}	3.70	2.98	-
		p	p<0.01	p<0.01	-
		Δ	18.77	17.07	-
	Elderly: Contralateral-ipsilateral	t_{361}	5.32	6.95	-
		p	p<0.01	p<0.01	-
		Δ	24.43	36.07	-
	Young adults: Contralateral-ipsilateral	t_{361}	3.02	5.09	-
		p	p<0.01	p<0.01	-
		Δ	8.41*	15.98	-

The values marked with * represent values in the range of the calibration error, and therefore even though they are statistically significant, the size of the effect in this case is considered negligible.

Case Studies

Due to the large variability among stroke survivors and their individual deficits, we analysed their results separately, in a case series analysis, where their individual results are compared to the results' distribution of the young adults, without analysing them as a group. This enabled us to profile each stroke survivor separately and identify individual impairments. The same method of evaluation may be also implemented for the elderly or any individual with suspicion of proprioceptive impairments. To demonstrate this analysis, two examples of stroke survivors are presented and discussed in this section. The results of all the stroke survivors are summarized in table 5.

Fig. 6-7 present two examples of the results of two different stroke survivors. The examined results are of MAE, Bias and MVE and they are depicted compared to the results of the young adults. To represent the distribution of each metric for the young adults, we assumed a normal distribution of the MAE, bias and log-transformed variability metrics. We plotted a normal distribution with the mean and variance from the sample of young adults, and integrated over the same distribution to calculate the cumulative percentage of the metric of the stroke survivors compared to these distributions. To determine the extent of potential proprioceptive, motor or cognitive impairments, we compared the results of all examined conditions. We repeated the process for all targets in all conditions. Then, we compared the six paired comparisons to attempt to pinpoint the sources of impairment: proprioception, transmission, memory, or motor execution. For this example, we arbitrarily chose a percentile of at least 90% in at least 2 of the targets as a suspect for an impaired condition, but future clinical studies are needed to determine the actual threshold to be used in clinical assessments. Fig. 6 describes the results of EDMS, a male stroke survivor aged 54 at the time of the assessment, who had an affected left limb, and was evaluated

one-month post stroke. He is a diabetic and was receiving treatment at the time of the analysis. He experienced an ischemic stroke in the thalamus. He was assessed with Fugl-Meyer and his lower limb results included 9/12 in sensation, 20/20 detection of passive movement and scored 33/34 in the motor assessment of the lower limb. He had an overall score of 26/30 in the MoCA (Montreal Cognitive Assessment), which is in the normal range (Jaywant *et al.*, 2019). First, conditions AU and AA both revealed large MAE and bias in most of the targets, suggesting an impairment in the proprioceptive input of the affected (left) limb. Second, we compared conditions AU and UU and in both found large MAE and bias, suggesting a motor impairment of the unaffected (right) limb. Third, we compared between conditions UA and UU, and found smaller bias and MAE in the UA condition compared to UU, suggesting that there was no proprioceptive impairment of the unaffected (right) limb. Forth, we compared the conditions UA and AA and once again since the results of the conditions were not consistent because UA provided values in the normal range, and AA provided three extreme values in MAE and bias, so we could not conclude that there was a motor impairment in the affected limb. Fifth, we compared the conditions UU and AA to identify a cognitive deficiency in memory. Moreover, if we examine the MVE values, we notice that their values were enlarged in targets 1,3 and 4 in AA and targets 2 and 4 in UU emphasizing the cognitive deficiency of the participant, since in some targets the variability was enlarged and the matching positions were more scattered relative to the targets, suggesting that the participants did not remember where to place his limbs, so the positions were more scattered. Lastly, we compared UA and AU and since the results of AU presented enlarged bias and MAE and UA did not, we may conclude that there was no impairment in transmitting spatial information from one limb to the other in both directions, but only from the affected to the unaffected limb. Note however that the AA condition was performed last, at the end of the evaluation and performance in this condition

could be affected by fatigue, and hence, to validate the diagnosis it would be advisable to repeat the entire procedure on a different day in a different order, or separate the assessment in two sessions, where the first examines the contralateral matching and the other the ipsilateral matching. To conclude, without accounting for possible confounding effects of fatigue, this individual likely suffers from proprioceptive impairment in the affected limb and a partial motor impairment in the unaffected limb.

Fig. 7 describes the results of another stroke survivor, ZK, a 62 male with an affected left side. Unlike EDMS, the bias and MAE results of ZK were almost universally enlarged (besides the results of targets 2 and 4 in AA and targets 2 and 3 in UU), ranking above 90% of the cumulative results of the young adults. Because the result values were so enlarged across all conditions, we could not isolate a specific impairment like we could for EDMS; in this case, there were several impairments that were reflected in the overall results. It is important to note that ZK has relatively small MVE values, across all conditions (besides targets 2 and 4 in UU), indicating that he was very consistent with his matchings, but very far away from the target.

To conclude, our proposed method and protocol can help to identify the source of the impairment in some of the cases. However, there are combinations of cognitive, sensory, and motor impairments that cannot be pinpointed beyond the general assessment that the participant has large errors when attempting to match or recall the position of their lower limbs.

Table 5 summary of the stroke survivors' results. The values represent the cumulative probability of the stroke survivors compared to the distribution of the young adults

Participant	Age (years)	Impaired limb	Metric	AA [%]				UU [%]				AU [%]				UA [%]				
			Target	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
ZK	62	Left	MAE	99	44	100	91	100	65	62	100	98	96	92	100	100	100	100	100	
			Bias	98	5	100	76	100	32	53	100	98	97	90	100	100	100	100	100	100
			MVE	39	86	72	55	70	92	77	100	10	2	7	29	6	6	2	2	
RAS	68	Right	MAE	56	27	39	11	7	76	79	54	58	30	17	25	99	51	87	99	
			Bias	75	16	79	19	13	94	87	52	59	26	11	19	98	58	90	99	
			MVE	4	32	43	5	7	79	62	62	3	35	37	63	60	48	12	66	
SBS	65	Right	MAE	74	98	100	76	36	89	100	24	15	42	21	26	40	12	2	8	
			Bias	75	99	100	26	22	97	100	19	14	54	24	23	49	23	2	14	
			MVE	100	71	100	99	6	91	81	33	4	4	0	74	11	0	10	6	
EIS	73	Right	MAE	-	-	-	-	93	100	99	48	98	100	12	75	-	-	-	-	
			Bias	-	-	-	-	97	99	100	56	98	100	7	74	-	-	-	-	
			MVE	-	-	-	-	38	100	68	99	35	11	5	1	-	-	-	-	
EDMS	54	Left	MAE	97	84	100	100	4	100	92	97	96	91	5	97	69	51	52	36	
			Bias	93	48	100	100	8	27	91	93	97	93	2	97	48	58	60	22	
			MVE	100	73	95	100	0	99	68	98	0	10	0	5	69	1	1	61	

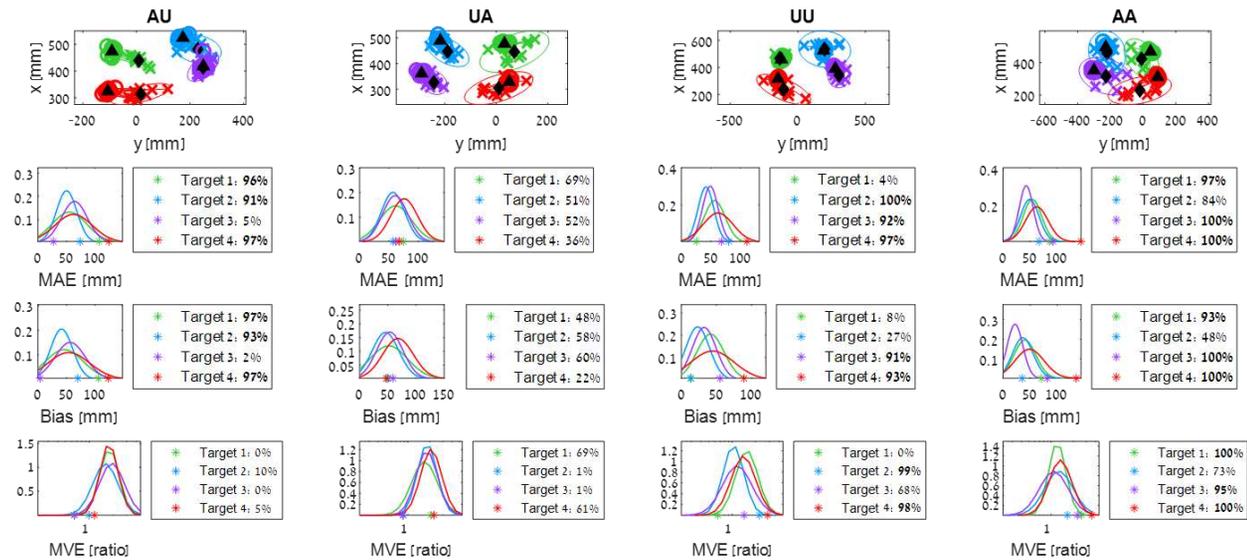


Figure 6 EDMS. The results of the stroke survivor in all the conditions (and their order from left to right). The bell shaped plots represent the distribution of the results of the young adults in every target of all conditions, and the cumulative distribution percentage of the individual results of EDMS are presented with ‘*’, as well as their value. The target colors are consistent across all conditions and plots.

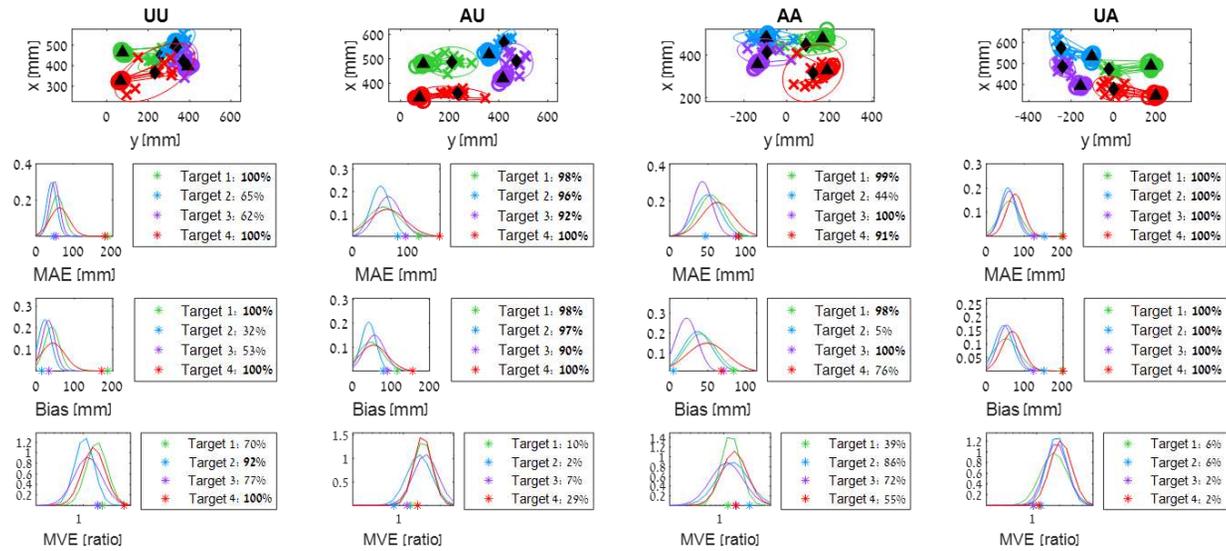


Figure 7 ZK. The results of the stroke survivor in all the conditions (and their order from left to right). The bell shaped plots represent the distribution of the results of the young adults in every target of all conditions, and the cumulative distribution percentage of the individual results of EDMS are presented with ‘*’, as well as their value. The target colors are consistent across all conditions and plots.

Discussion

In this work we present a novel quantitative tool for the assessment of lower-limb proprioception that is based on contralateral and ipsilateral position matching for both the dominant and non-dominant lower limbs in young adults and elderly, and the unaffected and affected limbs of stroke survivors. To the best of our knowledge, this study is the first attempt to develop a quantitative assessment that differentiates between sources of impairment that may affect lower limb function. We demonstrated the tool on young adults, elderly, and stroke survivors, mainly focusing on the grouped differences between the elderly and the young adults. The most pronounced differences in MAE and bias were in the contralateral matching conditions, particularly in ND, suggesting that with ageing, transition of spatial information from one hemisphere to the other becomes more challenging. These results were not demonstrated in all elderly participants, hence not every elderly person developed impairments with age. To detect potential individual impairments, we conducted a case series analysis, where we compared the overall individual results of two stroke survivors to the results of the young adults. In our assessments, we treated relatively (to the young adults) enlarged MAE, bias, and MVE values as indicators of potential impairments.

Approach

The approach of the current work is inspired by the work of (Leibowitz *et al.*, 2008), where an automated tool for upper limb proprioception was presented by conducting contralateral hand end point position matching tests with young adults and stroke survivors. We conducted a lower limb assessment of the end point position of the toe, allowing us to assess the position sense of the whole lower limb. Due to the effect of proprioception on active gait, we decided to conduct the assessment in the sagittal plane, which is in the plane of walking progression. Therefore, we chose

to conduct the assessment with the participants laying blindfolded on their side. Moreover, since the end point placement is influenced by one's motor abilities, we also conducted an ipsilateral assessment of each lower limb, and then compared the results of the contralateral and ipsilateral conditions to identify proprioceptive, motor and cognitive impairments. The suggested tool expands the idea of (Leibowitz *et al.*, 2008) to the lower limb, and considers also the motor and cognitive abilities as well.

In previous works, various position matching tasks were commonly performed to assess proprioception among young adults, mainly focusing on different tasks and limb preference in the performance of a particular joint. Contralateral and ipsilateral as well as contralateral memorized position matching tasks were performed with the upper and lower limb, where targets were sensed and memorized with one limb and its location and then reproduced with the same or contralateral limb (Adamo and Martin, 2009),(Goble and Brown, 2007), (Goble and Brown, 2008),(Goble and Brown, 2009), (Goble, Lewis and Brown, 2006), (Goble, 2010),(Kaplan *et al.*, 1985),(Gurari *et al.*, 2018).

The most common proprioceptive assessment focused on a particular joint of the upper (wrist, elbow) or lower limb (knee, ankle) and focused primarily on the asymmetries between the unpreferred and preferred limbs in position matching tasks. The suggested tool, as well as the tool of (Leibowitz *et al.*, 2008), relies on position matching of an end point position of a limb, rather than angular joint position. This method of proprioception assessment is considered more ecological and more representative of real-life activities, where the final position of the limb during an activity might be more valuable than the joints' angles that enabled this position. In previous works of the lower limb, particularly works of the knee (Study, Nitsure and Prabhu, 2017) and ankle (Yasuda *et al.*, 2014),(Forestier, Teasdale and Nougier, 2002),(Iandolo *et al.*,

2018),(Boisgontier and Nougier, 2013a),(Boisgontier and Nougier, 2013b),(Boisgontier *et al.*, 2012), the movement was restricted to the examined joints, allowing the participants to focus and control only one joint instead the complete length of the limb, which enabled the participants to isolated the proprioceptive sensation of only one joint. Our assessment, on the other hand, did not require focusing only on a particular joint, but on the end point position of the limb. To do so, participants were required to use the proprioceptive feedback from all lower limb joints and they could adjust each joint as they saw fit. This characteristic of the tool makes it more relevant to the functions of daily lives.

Young adults

We tested three groups of participants: young adults, elderly, and stroke survivors. The young adults represented the control group and the “healthy norm”, to whom we compared the results of the elderly and stroke survivors to identify potential impairments, which allowed us to validate the efficiency of the suggested tool. But before comparing their results to the results of the elderly, their results should be discussed separately. As an individual group, the young adults had very similar MAE and bias values in ipsilateral matching task conditions (NN and DD) and in contralateral matching task conditions (ND and DN) (Fig. 5.A-B). Contralateral position matching relies on sensing the target’s position with one limb and transferring this information to the contralateral hemisphere, so the contralateral limb could execute the matching, which requires remapping of the information (Iandolo *et al.*, 2018),(Lloyd *et al.*, 2003). In contrast, in the ipsilateral position matching task, the sensed information is memorized, and then the same limb that sensed its position executed the matching. This suggests that the transfer of information is more prone to error than its memorization.

The MAE values of the young adults represent the natural deviation of a healthy participant without any proprioceptive impairments. Our planned comparisons analysis of MAE did not indicate a significant difference between the contralateral and ipsilateral tasks, suggesting that the observed variability in the contralateral conditions was not significantly larger than in ipsilateral conditions. This coincides with the results of (Gurari *et al.*, 2018), where the memorization of a forearm position produced similar accuracy results as sensing the target position contralaterally. In other previous works of the upper limb, contralateral tasks produced larger absolute error values among healthy adults where the proprioception of the angle of the elbow (Goble, 2010), and wrist (Adamo and Martin, 2009) joints were assessed. It is assumed that tasks that involve memorization were less challenging since they involve less inter-spherical communication, while contralateral position matching tasks involved both hemispheres and transferring position information from one hemisphere to the other (Goble, 2010). This contradicts our MAE results; hence we did not find a significant difference between both tasks in the young adults group. The ipsilateral task in our assessment required the participants to sense the end point position by receiving feedback from all the lower limb joints and not a particular limb, making the ipsilateral task more difficult. The participants were not guided to use a certain strategy, so they were not asked to focus on the orientation of their joints during the assessment, but some of them reported using this strategy post-assessment. This difference in our assessment could reduce the difference in MAE between the contralateral and ipsilateral tasks.

The bias represents the overall deviation (constant error) of the position matching task considering the direction of the errors. The bias results reflected a difference of 16 mm between the contralateral task and the ipsilateral task in the young adults. In previous works of both the upper (Adamo and Martin, 2009),(Goble and Brown, 2007),(Goble and Brown, 2008) and lower

limbs (Yasuda *et al.*, 2014),(Forestier, Teasdale and Nougier, 2002), bias values were evaluated using a constant error. The constant error presented the overall deviation from a certain target, and considered the direction of the error. As previously mentioned, most assessments in upper and lower limb proprioception relied on joint angles, enabling the bias to be either negative (undershoot) or positive (overshoot) (Yasuda *et al.*, 2014),(Forestier, Teasdale and Nougier, 2002),(Adamo and Martin, 2009),(Goble and Brown, 2007),(Goble and Brown, 2008). In our assessment, the bias is calculated in a two dimensional plane, producing solely positive values. In (Goble and Brown, 2008) it was suggested that overshoot occurred when a proprioceptive target was sensed, while undershooting occurred in visual targets due to the difference in modalities between the kinaesthetic and visual spaces. Another study suggested that undershooting of the results may be caused due to passive movement of the limb to the target (Yasuda *et al.*, 2014). In our study, all target limbs were moved passively, but the test limb was moved actively by the participant, so the differences that we found in the bias may be a result of different movement types in the targeting phase and the matching phase of the evaluation, along complex processing in contralateral matching.

Limb preference was heavily investigated in upper and lower limbs as well. In both task types, the preferred test limb was the non-dominant limb (Iandolo *et al.*, 2018),(Goble, 2010),(Goble and Brown, 2008). In (Goble and Brown, 2008), right limb dominant participants were assessed and it was suggested that the proprioceptive centre that is placed in the right hemisphere is the cause of this preference. However, no significant differences were identified regarding the proprioceptive target limb in this work, both as a main factor and in interaction with group type, indicating that the young adults did not have a preferred limb for sensing the target position, and in extent, did not have a preferred active limb to execute the matching, both in the contralateral and ipsilateral

tasks. This inconsistency with previous work could be a result of the lack of joints restrictions and the difference between evaluating orientation instead of planar position. Recently, an ipsilateral and one dimensional end point matching of the foot was evaluated using two targets (Ofek, 2019). They found a significant difference between the non-dominant and dominant limbs only in the further target and no significant differences in the closer target. In the upper limb, when contralateral matching was conducted using the placement of the hands, no significant differences were found between both hands in the group of the young adults (Leibowitz *et al.*, 2008), (Schaap *et al.*, 2015). This inconsistency implies that spatial positioning may produce different results than joints' angles assessment. Further assessment of end point positioning with joint restrictions could be informative regarding both placement and orientation of the limb in general, and of the joints in particular.

Elderly

The group of the elderly represents a group that is closer in age to the group of the stroke survivors, but with no stroke or severe brain injury history. It was to be expected to find pronounced variability among the group participants, since not all elderly develop motor, cognitive or proprioceptive impairments, particularly in such small group size. The results in Fig. 5.A-B present the expected variability among the elderly, since it is clear that some elderly participants had similar and in some cases better results than the young adults by having smaller MAE and bias values, while some elderly had very large MAE and bias values. This noticed variability indicated that the suggested assessment tool is successful in identifying impairments of the aging process.

Both MAE and bias produced significant differences between the contralateral and ipsilateral position matching among the elderly. In this case and unlike the young adults, it corresponds to the results of healthy young adults from previous works of the upper limb (Goble, 2010), (Adamo

and Martin, 2009) and lower limb (Iandolo *et al.*, 2018). The more pronounced difference between the task types could be attributed to the aging process that emphasises the deterioration in some participants. An fMRI study with young adults conducting ipsilateral and contralateral position matching tasks found that in contralateral position matching, more brain areas were activated in both hemispheres, indicating that contralateral matching was more complex for execution (Iandolo *et al.*, 2018). Ageing could affect certain areas of the brain that make executing this task even more difficult and could increase the errors as well. Adding fMRI scans as used in (Iandolo *et al.*, 2018) to our assessment of the elderly could provide additional information regarding which brain areas deteriorate in aging and affect the proprioceptive sense.

As previously, similarly to the young adults, we did not have a reason to believe that the elderly had a preferred limb to conduct the assessment, as the effects of proprioceptive input and the interaction of group type with proprioceptive input were not significant.

Young adults and elderly

In this work we present a novel tool for lower proprioception assessment, based on contralateral and ipsilateral position matching tasks. The tool and its assessment protocol were designed to isolate proprioceptive, motor and cognitive impairments of elderly and stroke survivors. To validate that we compared the results of the elderly to the results of the young adults. The main differences between the groups were found in MAE and bias in the contralateral task and conditions. Previous studies presented similar contralateral and ipsilateral evaluations in lower limb joints. In (Kaplan *et al.*, 1985) elderly and young adults were asked to recreate and match knee joint angles and significant differences were found between the groups in ipsilateral position tasks, while in (Boisgontier and Nougier, 2013a) a contralateral position matching evaluation of the ankle joint was conducted and significant differences were found between the young adults

and elderly in metrics of total error (similar to MAE), bias and variable error (similar to MVE), but they did not perform an ipsilateral assessment. Another lower limb focused study examined several age groups in ipsilateral position matching of the ankle, and revealed significant differences between the young adults and the middle aged groups, but not the elderly (Deshpande *et al.*, 2003).

An upper limb study that examined ipsilateral and contralateral position matching of the hand in elderly and young adults examined the three dimensional placement of the hands (Schaap *et al.*, 2015). By evaluating the absolute error, they did not find significant differences between the groups in the ipsilateral task, but they found enlarged errors in the contralateral task for both groups, with the elderly producing significantly larger error. These results resemble our results of MAE in the comparison between the groups in the contralateral matching, but not in the ipsilateral matching. They suggested that because they did not examine position matching in a gravity free protocol, this protocol influenced the error values in both tasks, since the protocol required more effort.

The differences in errors were pronounced in the contralateral position matching task, suggesting that the contralateral assessment distinguishes between the two groups. Hence, contralateral evaluation could be used as a screening phase in the process of somatosensory assessment. Our assessment consisted of four different conditions of forty trials each and could inflict fatigue. To avoid unnecessary assessments, implementation of the tool in the clinic could begin with contralateral position matching for identifying potential proprioceptive disorders. If such suspicion rises, the patient would be invited to complete their assessment with ipsilateral position matching, to possibly (but not necessarily) exclude motor disorders and cognitive confounds as was demonstrated in the case study of EDMS and ZK.

Interestingly, MVE yielded a different picture than the MAE and bias. The only significant effect was noticed in the task type, suggesting that both the elderly and young adults experienced more difficulty in the contralateral tasks, which was expressed in larger variability in the matchings; this was not surprising since this task required transmitting spatial information from one hemisphere to the other. As previously mentioned, (Iandolo *et al.*, 2018) examined the activated brain area while young adults were conducting ipsilateral and contralateral position matching. They found that a wide spread of brain areas was activated across both hemispheres in contralateral matching, emphasizing its complexity even in a young brain. It can be assumed that in an aged brain, this task would become more difficult. This also suggests that the elderly and young adults had similar variability in their matching process. In the case of impaired elderly, it would come across as large but similar MAE values in a similar direction, enlarging the bias, but reducing the variability because the test matchings would be closer to one another, less scattered but still far from the target. In (Boisgontier and Nougier, 2013a) concurrent contralateral position matching of the ankle in two speeds, natural speed and enhanced speed, was conducted with the non-dominant limb as the target limb. They found larger variability among the elderly in this assessment, particularly in higher speed, suggesting that the elderly relied more on working memory to achieve the favourable result. In a different study, contralateral matching of the ankle was examined in combination with cognitive tasks (Boisgontier *et al.*, 2012). The results showed no significant difference in variable error between the elderly and young adults, but showed significant differences between the different tasks, as did we. This suggests that variability may be dependent mainly on the task complexity, since our assessment was more challenging in terms of positioning the end point of the limb and receiving proprioceptive feedback from multiple joints (Schaap *et al.*, 2015) in a non-restricted workspace, opposed to a single joint.

Stroke survivors

Unlike the elderly and young adults, the stroke survivors were presented without a group summary statistics due to the fact that each stroke survivor had a different and unique neurological impairment. We presented a detailed assessment of two different stroke survivors. We suspect a proprioceptive impairment of the affected limb, an additional motor disorder of the non-affected limb that may be related to uncrossed corticospinal tracts (Kim *et al.*, 2003), and a memory cognitive disorder for participant EDMS. However, we could not isolate the source of the impairments of ZK, since almost all his results were enlarged, and possibly, this participant suffered from all these types of impairments (proprioceptive, motor and cognitive) simultaneously. A possible alternative for isolating the potential proprioceptive impairment is a passive assessment, where the participant would not actively move the test limb for the matching. We piloted this type of assessment with young adults (results not reported), but the protocol required the examiners to move the test limb in different directions and recording the position of the limb following a verbal cue from the participants, and the resulting protocol was too long to be feasible for testing on a population of elderly and stroke survivors.

Among the five stroke survivors, ZK and EDMS, whose results are presented in this paper, were the only stroke survivors who completed the assessment and presented MAE and bias values above the 90 percentage in at least two targets, relative to the distribution of the young adults in several conditions and both are impaired in their left limb (SBS had 21 excluded trials in NN so we did not discuss their results in full). A study, targeting stroke survivors with different traumas, examined the capability of the stroke survivors to mirror the position of their fingers contralaterally and found that larger errors were conducted by the stroke survivors with the unaffected limb (Dukelow *et al.*, 2010). Moreover, an fMRI evaluation was conducted during contralateral and

ipsilateral position matching tasks, and they discovered that the main regions responsible for position sense were in the right hemisphere (Iandolo *et al.*, 2018). Following this, brain damage, such as stroke, affecting the right hemisphere may lead to a distorted sense of limb position and proprioceptive impairment. It is important to note, that EDMS had an ischemic stroke in the thalamus. Case studies that examined stroke in this area, both clinically (Kim, 1992) and both in a quantitative method using a KINARM robot (Kenzie *et al.*, 2014), reported that damage in the thalamus caused proprioceptive deficits, yet it depended on lesion volume and additional factors. This emphasises the importance of evaluating each stroke survivor separately.

Despite that we could not isolate particular impairments in the case of ZK, we were successful in suggesting a diagnosis with EDMS, suggesting the effectiveness of our method to identify proprioceptive impairments, along with the motor and cognitive disorders as well.

Limitations

Several limitations should be taken into consideration regarding our proposed tool for the assessment of lower limb proprioception. The most important one is the duration of the assessment – the procedure took on average 53 minutes for young, 57 minutes for the elderly and stroke survivors (who completed all four conditions), during which the participants were required to remain focused for the while laying down blindfolded. Such prolonged assessment may cause mental fatigue. This limitation can be partially addressed by separating the assessment into two sessions of contralateral and ipsilateral assessments. Another limitation of the assessment protocol was that the stroke survivors were required to lay on their affected side, which may cause pain. During our assessment, one of the stroke survivors could not complete the full assessment due to pain to the affected side.

In addition, we did not use a passive assessment. Initially, we planned to conduct at least one condition where one limb is placed on a target and then the test limb is moved passively by the examiner until the participant cues them to stop. In the assessment of young adults we conducted a passive assessment as well, but it was too long and challenging to conduct with elderly and stroke survivors. Also, preliminary analysis of this test did not provide an additional insight to the existing work so these results are not reported in this work. However, the absence of a passive assessment makes it more challenging to isolate the proprioceptive impairment. In previous studies, a passive evaluation was usually conducted using robotic devices (Gurari *et al.*, 2018).

Finally, unlike many previous works, our approach did not focus on a particular joint but on the end point position of a limb. This approach did not enable us to isolate potential impairments of particular joints but to identify a general disorder. If a disorder is identified, further examinations can be conducted to identify the source of the impairment.

We used magnetic trackers, which are sensitive to magnetic noise and disruptions, and the assessments were conducted in an environment with some ferromagnetic metals in the surroundings, and the calibration covered only a part of the environment. An alternative magnetic tracking can be a robotic exoskeleton, as commonly used in the upper limb (Dukelow *et al.*, 2010),(Gurari *et al.*, 2018),(Sketch, Bastian and Okamura, 2018), but one has to make sure that a full range of motion is tested for the assessed limbs and joints (Maggioni *et al.*, 2016). Another potential solution is marker-based movement tracking (Khan *et al.*, 2020), or marker-less tracking using image processing and deep-neural network (Mathis *et al.*, 2018).

Furthermore, no clinical assessment of proprioception was conducted with the participants. The stability of the elderly and stroke survivors was examined by a physical therapist in a corresponding research. This work suggests an assessment tool and successfully validated it with

the elderly and stroke survivors. Future work could include using the suggested tool and comparing it to clinically common assessments and the connection between the results of the tool and a patient's gait and stability.

Future work

In the future, studies with large populations of elderly and stroke survivors are needed as well as in individual case series analysis and not solely as a demonstration. It is also important to include clinical evaluations of sway, tactile sensation, and gait analysis to have a more detailed idea regarding each individual and the severity of their potential impairments. Additional work can be conducted to improve the suggested tool. One possibility is to conduct a similar assessment while the participants are sitting on a chair. In this case, a similar assessment can be conducted to the assessment of (Ofek, 2019) if conducted in one dimension using a force plate. An expansion of such an assessment to a planar plane can be conducted with a mirroring assessment, as in (Dukelow *et al.*, 2010). Another potential extension of the tool and research is an assessment of specific joints of the lower limb, which can be achieved by restricting the movement of the hip, knee, and ankle joints in the same assessment, where the participants still have to match and recreate the same target positions. This assessment might be very long since more conditions would be examined, so it would have to spread across several days to avoid fatigue and unnecessary testing in case the results do not suggest a potential impairment.

Conclusions

Somatosensory impairments are often neglected and overlooked in the rehabilitation process, partially due to the lack of available objective and quantitative methods for proprioception assessments. In this work we propose a setup and protocol for the assessment of lower limb

proprioception, and demonstrate it with two age groups – young adults and elderly – using contralateral position matching and ipsilateral matching tasks. The contralateral assessment yielded the most pronounced difference between the groups. Moreover, by comparing the characteristics of the tasks, proprioceptive, motor and cognitive impairments could be identified in elderly and stroke survivors, compared to young adults. The results of this work may improve the current understating of lower limb impairments due to ageing and stroke, and improve current treatment methods.

List of Abbreviations

D: Dominant limb

N: Non-Dominant limb

A: Affected limb

U: Unaffected limb

DD: Dominant-dominant, dominant limb is placed above a target, moved away and then actively returned to the memorized position.

NN: Non-dominant-non-dominant, non-dominant limb is placed above a target, moved away and then actively returned to the memorized position.

DN: Dominant-non-dominant, the dominant limb is placed on a target and then the non-dominant limb is actively moved to match its position.

ND: Non-dominant- dominant, the non-dominant limb is placed on a target and then the dominant limb is actively moved to match its position.

UU: Unaffected-unaffected, unaffected limb is placed above a target, moved away and then actively returned to the memorized position.

AA: Affected-Affected, affected limb is placed above a target, moved away and then actively returned to the memorized position.

UA: Unaffected-affected, the unaffected limb is placed on a target and then the affected limb is actively moved to match its position.

AU: Affected-unaffected, the affected limb is placed on a target and then the unaffected limb is actively moved to match its position.

MAE: Mean absolute error

MVE: Mean variable error

Declarations

Ethics approval and consent to participate

The protocol and the consent form were approved by the Human Participants Research Committee of Ben-Gurion University of the Negev, Be'er-Sheva, Israel. All participants signed an informed consent before participating, and were reimbursed for their time.

This study was approved by the Local Human Research Ethics Committee (Shamir Medical Center affiliated to Tel-Aviv University) and conducted in conformity to the standards set by the latest revision of the Declaration of Helsinki, including for registration in the Israeli database MOH_2018-02-14_002188. Participants were fully informed about the nature and the aim of the study and gave their written informed consent to participate.

Consent for publication

Not applicable.

Availability of data and materials

The data that was used for the analysis is available at:

<https://www.dropbox.com/sh/hzwqzun7nieiy57/AAAEXEm0znBeu28h6BNBG1Yoa?dl=0>

The authors will be happy to answer any questions regarding the presented work by e-mail.

Competing interests

The authors declare that they have no competing interests.

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Author Contributions

AM, YK, SBH and IN designed the protocol according to the needs of the study. YK and SBH recruited the elderly and stroke survivors in this study. AM created environments for data collection and calibration, and for the analysis of the results. AM performed the experiments and collected the data. AM, SBH and IN interpreted the results, AM wrote the first draft of the paper and AM, YK, SBH and IN edited the paper and the final version.

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