Measuring upper limb active joint position sense: Introducing a new clinical tool - The Upper Limb Proprioception Reaching Test

ABSTRACT

Background

Proprioception is our sense of body awareness, including the sub-category of active joint position sense (AJPS). AJPS is fundamental to joint stability and movement coordination. Despite its importance, there remain few confident ways to measure upper limb AJPS in a clinic.

Objective

To assess a new AJPS clinical tool, the Upper Limb Proprioception Reaching Test (PRO-Reach; seven targets), for discriminant validity, intra-rater and absolute reliability.

Design

Cross-sectional measurement study.

Methods

Seventy-five healthy participants took part in a single session with 2 consecutive evaluations (E1 and E2) (within-day reliability). Twenty participants were randomly selected to perform a dominant shoulder fatigue protocol (discriminant validity), whereafter a third evaluation was repeated (E3). The PRO-Reach was analyzed with paired *t* tests (discriminant validity), intra-class correlation coefficients (ICCs) and minimal detectable change [MDC]) (intra-rater: within-day and between-trial relative and absolute reliability).

Results

The PRO-Reach supports moderate (mostly superior targets) to excellent (mostly inferior targets) reliability. Between-trial ICCs (T1 / T2 / T3) varied between 0.72 and 0.90, and within-day (E1 / E2) ICCs between 0.45 and 0.72, with associated MDC_{95} values (3.9 to 5.0 cm). The overall scores (seven targets) supported the strongest within-day reliability (ICC = 0.77). The inferior targets demonstrated the highest between-trial and within-day reliability (ICCs = 0.90 and 0.72). A fatigue effect was found with the superior and superior-lateral targets ($P < .05$).

Conclusions

The inferior targets and overall scores demonstrate the strongest reliability. The use of the PRO-Reach tool may be suitable for clinical use upon further psychometric testing amongst pathological populations.

Level of evidence: Level III cross-sectional study.

Key words: Upper limb, active joint position sense, proprioception, validity, reliability

List of abbreviations

AJPS = active joint position sense

E1 = first evaluation

E2 = second evaluation 30-minutes later

E3 = final evaluation following a muscular fatigue protocol

GH = glenohumeral joint

ICC = intraclass correlation coefficient

*Quick*DASH = *Quick* Disability of the Arm, Shoulder, or Hand

MD = movement disorders

MDC90 = minimal detectable change at 90% confidence

MDC95 = minimal detectable change at 95% confidence

MVIC = maximum voluntary isometric contraction

SEM = standard error of measurement

RM = repetition maximum (maximal load that a person can lift once in their available range of motion)

PE = proprioception error

PRO-Reach = Upper Limb Proprioception Reaching Test

PRO-Reach Target Directions

S = Superior

SLD = Superior Lateral Dominant

LD = Lateral Dominant

ILD = Inferior Lateral Dominant

SLND = Superior Lateral Non-Dominant

LND = Lateral Non-Dominant

ILND = Inferior Lateral Non-Dominant

HIGHLIGHTS

- The Upper Limb Proprioception Reaching Test (PRO-Reach) has potential to be clinically applicable.

- It is a user-friendly tool, using reaching movements to evaluate shoulder and upper limb active joint position sense.

- Overall, the PRO-Reach supports good within-day reliability (ICC=0.77) when evaluating all seven targets.

- Further testing of the PRO-Reach is warranted for validity, reliability and responsiveness measures.

FOR REVIEWERS

What is already known on this topic:

Proprioception is a difficult and often abstract concept to quantify. Understood as our sense of joint and limb awareness, it helps to guide our movements and may prevent injury during everyday activities. There is growing support that movement disorders of the upper limbs and shoulders could result in a decreased sense of proprioception. There is also evidence that proprioception impairments can lead to injury. Thus, optimizing proprioception is often a rehabilitation goal for clinicians when addressing movement disorders and shoulder dysfunctions.

At present, there are limited reliable or valid methods for quantifying the sense of upper limb proprioception in a clinical setting. In addition, laboratory protocols for the measurement of upper limb proprioception are often time-consuming, involve computer-faced equipment and are not transferable to a clinic. There is currently a knowledge gap within the literature concerning the associated psychometric properties of such protocols or outcome measures. Furthermore, there is no Gold Standard for the measurement upper limb proprioception, more specifically active joint position sense, at this time.

What this study adds:

In order to address the current absence of clinically reliable and valid proprioception outcome measures for the upper limb, the purpose of this study was to develop a novel upper limb proprioception tool for the measurement of active joint position sense, a sub-modality of proprioception. This study presents the validity and reliability results of a newly developed clinically-friendly tool: Upper Limb Proprioception Reaching Test (PRO-Reach). The aim of this study is primarily to describe the process of development of the new clinical tool as well as to present the intra-rater reliability and discriminant validity. This will be accomplished via a within-day repeated measure protocol with the use of a shoulder muscle fatigue protocol for the evaluation of the discriminant validity. The results of our study will present a simple, reliable, cost-effective and clinically accessible tool for the measurement of upper limb active joint position sense.

INTRODUCTION

Proprioception is a somatosensory sense which contributes to the generation of our body image [1]. It is comprised of various sub-categories, including kinesthesia (our perception of movement), joint position sense (active and passive), and our sense of force (heaviness or effort) and velocity [2]. The sub-categories work collaboratively to maintain our body's biomechanical spatial properties [3] and neurophysiological stability [4, 5].

Proprioception is a key contributor to upper limb motor performance during activities of daily living (ADLs) or during sport and work[6, 7, 8]. The glenohumeral (GH) joint is the primary upper limb mover, and shoulder and upper limb proprioception deficits have been noted among individuals affected by shoulder pain [9, 10], instabilities [11-13], osteoarthritis [14], rotator cuff dysfunctions [15-17, 18] and in post-operative shoulders [12, 14, 19]. Proprioception deficits have also been suggested to cause a predisposition to shoulder injury [20].

It is understandable that the rehabilitation of proprioception is an important clinical goal following a shoulder or upper limb injury [9, 21]. Granted this importance, the measurement of upper limb proprioception by clinicians remains a challenge [22], as few clinically-friendly tools are available to measure this sense [22,23,24]. Currently, there is no universally accepted method that allows for an objective and precise evaluation of proprioceptive function [25-27]. In order to most closely resemble active and functional movements, the clinical assessment of upper limb proprioception should employ tests for measuring active joint position sense (AJPS) [5, 22].

As it is difficult to uncouple AJPS from our understanding of motor control [28], recent research has been moving away from evaluating AJPS at a single joint, towards appreciating the multisensory representation of an entire limb in space [29]. These evaluations are performed in a more controlled environment, however they use complex and computer-interfaced equipment that are seldom available for a therapist wanting to assess proprioception [30]. To our knowledge, there has yet to be a clinically-friendly way to measure upper limb proprioception in a clinical setting.

There have been efforts to quantify upper limb AJPS using clinical tools such as a goniometer [23, 31], inclinometer [23,18, 32-34], laser pointer [23, 35], an iPod touch [20] or photo analysis technology [31, 36, 37]. Yet even the current clinical protocols lack clear reporting of their methods and associated psychometric properties, making them difficult to reproduce and use. Furthermore, current AJPS protocols involve single plane movements only [23, 32, 33, 35-37] and use trigonometry to calculate the proprioception error [23].

It is also important to recognize that current methods for measuring upper limb proprioception do not mimic movements or positions from daily functional activities or sports. As the upper limb involves a chain of multiple mobile joints, it is essential to measure upper limb proprioception in a multiplanar perspective [38]. Proprioception assessments should reflect real world context [39] and maximise ecological validity [40, 41]. There is a clinical need for valid, reliable and functional tools [5, 24, 25] that can evaluate a change in upper limb proprioception over time.

In response to this need, the purpose of this study was to develop a new tool, the Upper Limb Proprioception Reaching Test (PRO-Reach), theorized to measure upper limb AJPS in a clinical setting, and to assess its psychometric properties (intra-rater reliability and discriminant validity). The PRO-Reach is designed to be a clinically practical tool, which uses functional reaching movements to measure upper limb proprioception. We hypothesize that the PRO-Reach will support good reliability (ICC = 0.75 – 0.90) [42] and will be able to identify the participants performing this test in a fatigued state. It has been recognized that muscular fatigue can adversely disturb the sense of proprioception, [3, 5, 43] by altering our sense of effort and representation in space [1].

METHODOLOGY

Development of the PRO-Reach

The PRO-Reach was conceptualized as a clinically-friendly tool, as it uses active and open-chained movements, theorized to promote a strong ecological validity [40]. The PRO-Reach

uses topo-kinesthetic movements towards a target [44], which utilizes specific neural pathways for spatial memory, involved in the memory of routes and movements (topo-kinesthetic memory) [45], which most resembles daily functional movements.

The PRO-Reach Tool

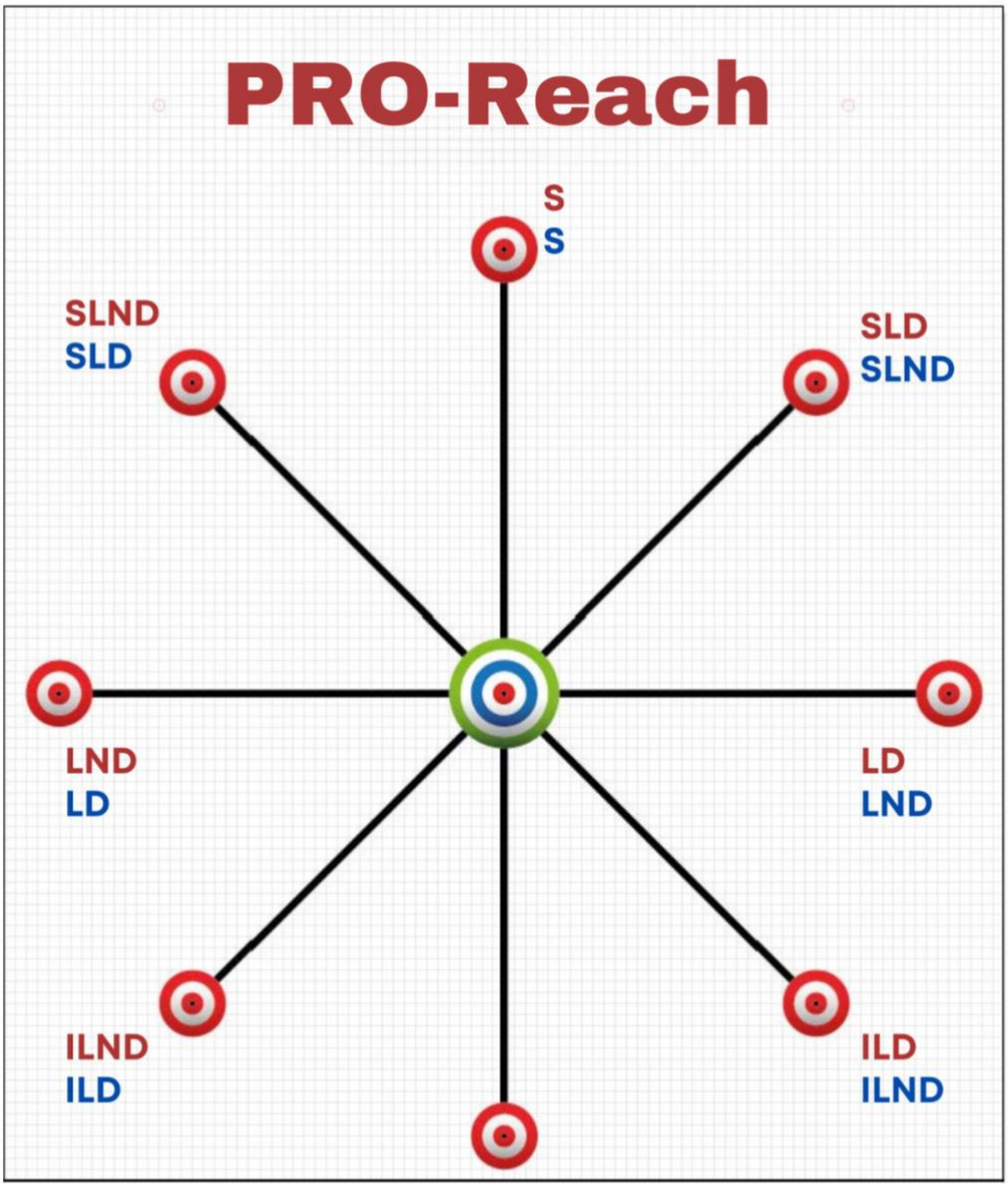
The PRO-Reach uses a plasticized poster (90 cm in length and 110 cm in height), printed on a grid pattern of 1 cm squared, for the ease of measurement of the PE. The poster is mounted on a wall with double-sided magnetic strips (ProMAG® Magnetic Tape; Marietta, OH, USA), to adjust to the height of the participant. The PRO-Reach uses stickers (0.6 cm round colour-coded, manually numbered 1-3) for the three reaching trials per target, and a standardized evaluation form (Appendix I) with instructions (Appendix II). Each participant is told that the purpose is to "evaluate your ability to reproduce movements in space" and are instructed to "memorize the position of your arm in space".

A total of seven targets in a star formation is used and the targets are named according to the direction of movement of the dominant shoulder (Figure 1). For example, the left-side of the PRO-Reach is dominant for left-handed participants, and the right-side of the PRO-Reach represent non-dominant (ND) cross-body movements, and vice-versa for right-handed participants (Figure 1). The targets are therefore named: superior (S), superior-lateral dominant (SLD) and non-dominant (SLND), lateral-dominant (LD) and non-dominant (SLND) and inferior-lateral dominant (ILD) and non-dominant (ILND). The (S) target is used to evaluate the reaching movements for both right and left-handed participants. During the evaluation, each participant was evaluated on 21 reaching movements in total, 7 targets with 3 reaching trials each. An evaluation of all 7 targets takes an estimated 25-30 minutes, including instructions, with each target taking less than 5 minutes to evaluate individually.

The participant performed three memorization trials, where they reached with their eyes open towards an indicated target. Once their index finger reached the center of the target, they would close their eyes and memorize their position in space for 5 seconds. Following the memorization trials, they would promptly apply a blind-fold with their non-dominant hand, and immediately perform three reproduction reaching trials towards the target (used to

measure the PEs) (Figure 2). No feedback or corrections are given during testing. After each reproduction reaching trial, the evaluator placed a numbered sticker (1 through 3) immediately above the nail of the index finger, without making contact. One target is evaluated at a time. The evaluator used a retractable fabric sewing measuring tape (Fabric Tailor Cloth Craft Measurement Tape) to measure from the center of the target, to the center of the sticker, representing the "proprioception error" (PE) in cm. For the purpose of this study, upper limb "proprioception acuity" [24] is the reaching accuracy of the participant during the reproduction movement towards a target. The absolute PE is understood as the absolute difference in centimeters (cm) between the reaching trial (when the index finger makes contact with the PRO-Reach) and the center of the referenced target.

Figure 1: The Upper Limb Proprioception Reaching Test



Direction of movement according to dominance

RIGHT-handed

LEFT-handed

S = Superior
SLD / ND = Superior Lateral Dominant / Non-Dominant
LD / ND = Lateral Dominant / Non-Dominant
ILD / ND = Inferior Lateral Dominant / Non-Dominant

Caption: *Visual depiction of the Upper Limb Proprioception Reaching Test (PRO-Reach), a plasticized poster of 90 cm in length and 110 cm in height, mounted on a wall with double-sided magnets. (Full colour)*

Figure 2: Upper limb reaching movement to assess the proprioception error (PE) with the PRO-Reach

Psychometric Evaluation of the PRO-Reach

Participants

Two locations (the Centre for Interdisciplinary Research in Rehabilitation and Social Integration (Cirris) in Québec City, Canada as well as at Ghent University in Belgium) were used for recruitment and testing. A convenience sample of healthy individuals was recruited through posters and e-mail distribution lists at *Université Laval* and the Cirris in Quebec City, Canada as well as at Ghent University in Belgium. Participants were eligible if they 1) were between the ages of 18 and 35, and 2) reported no musculoskeletal injuries to either the upper extremity or cervical-thoracic spine within the past two years, and 3) had no other major health concerns (signs, symptoms or diagnosis of a systemic or neurological pathology) that would prevent them from participating in the study.

Evaluator

One evaluator (A.L.A; with 5 years of clinical experience as a physiotherapist treating upper limb musculoskeletal injuries) performed the PRO-Reach evaluations in both locations. Assistance was provided by local students and colleagues for data collection and analysis. A familiarization period included two days of practice with ten Master students, for the evaluator (A.L.A) to become proficient with the PRO-Reach tool.

Study Design

A cross-sectional methodological study design.

Procedures

Participants were invited to participate in an assessment for a maximum of 120 minutes. All participants gave informed written consent, completed a health questionnaire, the *Quick* Disability of the Arm, Shoulder, or Hand (*Quick*DASH; score ranges from 0 [no disability]

to 100 [most severe disability]) questionnaire [46] and the Edinburgh Handedness Inventory for dominance [47]. The minimal clinically important difference (MCID) of 15.91 points of the *Quick*DASH [48] was used as a cut off score, to ensure participants did not report any upper extremity functional limitations. The *Quick*DASH has excellent test-retest reliability and longitudinal construct validity[49]. Each participant performed the PRO-Reach twice (Evaluation 1 [E1] and Evaluation 2 [E2]), with a 60-minute rest period between evaluations. The evaluations were performed by a single evaluator (A.L.A). The order of the targets were randomized using randomization software (https://www.random.org) [50] by an investigator not directly involved in the study.

Twenty participants from Cirris, Québec City, Canada were randomly chosen by selecting participant numbers from an opaque envelope, to participate in a third PRO-Reach evaluation (E3) following a shoulder fatigue protocol to assess the discriminant validity. The discriminant validity was also evaluated with the participant's dominant shoulder.

Fatigue Protocol

A fatigue protocol proposed by Ebaugh and colleagues [51] was used, which included the continuous completion of the following three tasks of the dominant shoulder in standing: 1) maintaining the arms elevated to 45° in the frontal plane and screwing a nut and bolt clockwise and counter-clockwise for 2 minutes (size M12×68, 0.085 kilograms [kg]), 2) raising and lowering of the arm against resistance in the plane of the scapula for 20 repetitions, and 3) raising and lowering the arm through a diagonal pattern against resistance for 20 repetitions. The resistance was set at 20% of the maximum voluntary isometric contraction (MVIC) of the abductor muscles of the dominant shoulder. This was evaluated according to the manual muscle testing protocol established by Hébert et al. (2012) [52]. The resistance was evaluated in kg, and 20% of the mean MVIC following 3 measurements was calculated and rounded up to the nearest kg. The corresponding hand weight was given to the participant. Participants continued the three tasks in sequence until they failed to correctly perform two tasks consecutively, as determined by the evaluator, or they reported a minimum of 16/20 on the Borg Rating of Perceived Exertion Scale (BRPE), ranging from 6 (no exertion) to 20 (maximum exertion). A score of 16/20 is theorized to represent an intensity

level of 80% 1 RM (maximal load that a person can lift once in their available range of motion) [53].

Sample Size and Statistical analysis

According to the COSMIN Checklist for methodological reliability studies, a sample size greater than 50 participants is considered to be good [54]. Therefore, a minimum of 50 participants was targeted for this study.

All statistical analysis was conducted using IBM SPSS® Software (version 26.0 for Mac; Armonk, NY) with an alpha level of 0.05. Descriptive statistics of the absolute PE (means $\pm$ standard deviations) were calculated across participants in cm. Each target produced three PEs per evaluation (trials: T1 / T2 / T3). The mean values per target per participant (mean PE) were used for inferential statistics, the between-trial (T1 / T2 / T3, per target) within-day (mean of the three trials at Evaluation 1 [E1] and mean of the three trials at Evaluation 2 [E2]), relative reliability calculations, and the absolute reliability measures. Moreover, the global mean PRO-Reach score (the average of the mean PEs of each target), was also used to establish the within-day reliability of the PRO-Reach.

Intraclass correlation coefficients (ICCs) were used to assess the relative reliability [55]. For the between-trial (T1 / T2 / T3) and within-day (E1 and E2) reliability, the three trials per target were used, and an $ICC_{3,k}$ (two-way random model with absolute agreement) was calculated. ICC values less than 0.5 indicate poor reliability, values between 0.5 and 0.75 indicate moderate reliability, values between 0.75 and 0.90 indicate good reliability, and values greater than 0.90 indicate excellent reliability [42].

To examine the absolute reliability, the degree to which repeated measures vary for individuals, the standard error of measurement (SEM) was calculated for each target and the global mean PRO-Reach score (all seven targets), as $SD \times \sqrt{1 - ICC}$ [56]. The SEMs were used for calculating the minimal detectable change (MDC_{95}) for each target and the global mean PRO-Reach score (all seven targets), which were calculated as $SEM \times 1.96 \times \sqrt{2}$, respectively.

Dependent samples *t*-tests were conducted to compare the PEs of each target and global mean PRO-Reach score (all seven targets) between the second evaluation (E2) and the post-fatigue evaluation (E3) of 20 participants, to quantify the discriminant validity. All data was tested to verify the distributional assumptions for the inferential statistical analyses.

RESULTS

Eighty participants were contacted for this study and five were excluded due to age and upper limb neurological symptoms, therefore seventy-five participants were included (Table 1). The *Quick*DASH score of all participants was lower than 0.9/100, reflecting normal shoulder function. Descriptive data of the PEs can be found in Table 2.

The evaluation time of the PRO-Reach tool took less than 5 minutes for one target, 12 – 15 minutes for 3 targets, and 25-30 minutes for the entire 7 targets of the PRO-Reach, including the time required for instructions and practice.

Table 1 Means and standard deviations of baseline characteristics of included participants

	All (n=75)	**Canada (n=36)**	**Belgium (n=39)**
Age	24.8 ± 4.7	27.3 ± 5.4	22.5 ± 2.2
Sex (male/female)	31/ 44	15/ 21	16/ 23
Height (cm)	171.8 ± 9.6	171.3 ± 10.7	172.2 ± 8.6
Weight (kg)	67.5 ± 13.7	68.2 ± 15.0	66.8 ± 12.6
Dominance (R/L)	61 / 14	27 / 9	34 / 5

***Caption**: n=sample size, (mean ± standard deviation), R=right, L=left.*

Table 2 Descriptive statistics of the mean proprioception errors (PEs) of the PRO-Reach in centimeters (mean ± standard deviation) for all participants (n=75) during the two evaluations

AJPS reaching movement	First Evaluation (E1) (n=75)	Second Evaluation (E2) (n=75)
S	4.5 ± 2.6 [0.5 – 13.0]	4.1 ± 2.1 [1.3 – 11.3]
SLD	4.8 ± 2.7 [1.3 – 12.1]	4.5 ± 2.4 [0.4 – 11.2]
LD	4.9 ± 2.5 [1.3 – 11.8]	4.7 ± 2.4 [1.3 – 15.3]
ILD	5.4 ± 2.7 [1.5 – 13.1]	5.6 ± 2.5 [1.0 – 11.4]
SLND	4.8 ± 2.4 [1.1 – 10.2]	4.7 ± 2.4 [0.9 – 9.5]
LND	4.6 ± 2.4 [0.7 – 14.0]	4.2 ± 2.2 [1.1 – 11.5]
ILND	5.7 ± 3.1 [1.1 – 12.9]	5.9 ± 3.0 [1.3 – 13.6]
Global mean PRO-Reach score (7 targets)	4.9 ± 1.3 [2.4 – 9.1]	4.8 ± 1.3 [2.4 – 8.3]

***Caption**: n=sample size*

Mean of three trials (T1 /T2 /T3) of each target of the PRO-Reach. The global mean PRO-Reach score reflects the mean proprioception error from all seven targets of the PRO-Reach.

PRO-Reach targets: Superior (S), Superior Lateral Dominant (SLD), Lateral Dominant (LD), Inferior Lateral Dominant (ILD), Superior Lateral Non-Dominant (SLND), Lateral Non-Dominant (LND) and Inferior Lateral Non-Dominant (ILND).

Reliability analysis

The intra-rater between-trial (T1 / T2 / T3) ICCs for each target ranged from 0.72 to 0.90, reflecting moderate to excellent reliability. SEM values varied from 1.4 cm (ILD target) to 1.9 cm (SLD target) (Table 3). The absolute reliability MDC_{95} values ranged from 3.9 cm (ILD target) to 5.0 cm (ILND target).

Table 3 Between-trial reliability (ICC values with 95% Confidence Interval) and absolute reliability in centimeters for the PRO-Reach (n=75)

AJPS reaching movement	SEM	MDC95	ICC values [95% Confidence Interval with range] (Trials: T1 / T2 / T3)	Significance *P*-value
S	1.7	4.5	**0.87** [0.67 to 0.94]	*P*<.001
SLD	1.9	4.4	**0.80** [0.66 to 0.89]	*P*<.001
LD	1.7	4.7	**0.82** [0.53 to 0.92]	*P*<.001
ILD	1.4	3.9	**0.90** [0.77 to 0.95]	*P*<.001
SLND	1.7	4.7	**0.72** [0.48 to 0.85]	*P*<.001
LND	1.6	4.5	**0.85** [0.73 to 0.92]	*P*<.001
ILND	1.8	5.0	**0.80** [0.63 to 0.90]	*P*<.001

Caption: *Absolute between-trial reliability of the PRO-Reach per direction of movement and composite scores during the first evaluation of shoulder proprioception (E1) between reaching trials (T1 / T2 / T3); AJPS =active joint position sense, ICC = intraclass correlation coefficient, SEM = standard error of measurement, MDC95 = minimal detectable change at 95% confidence.*

PRO-Reach targets: Superior (S), Superior Lateral Dominant (SLD), Lateral Dominant (LD), Inferior Lateral Dominant (ILD), Superior Lateral Non-Dominant (SLND), Lateral Non-Dominant (LND) and Inferior Lateral Non-Dominant (ILND).

Results from the ICCs for intra-rater within-day reliability (E1 and E2) for all targets can be found in Table 4. ICCs ranged from moderate (ICC = 0.45 – 0.70) to good (ICC = 0.77). The strongest reliability measures are reflected in the inferior targets; with the inferior lateral dominant (ILD) target (ICC = 0.72 [0.57 to 0.83]) and inferior lateral non-dominant (ILND)

(ICC = 0.65 [0.42 to 0.78]). The composite score of the PRO-Reach (all 7 targets) demonstrates overall good within-day reliability ICC = 0.77 [0.62 to 0.85].

Table 4 Within-day reliability (ICC values with 95% Confidence Interval) for the PRO-Reach (n=75) in centimeters

AJPS reaching movement	SEM	MDC95	ICC values [95% Confidence Interval]	Significance *P*-value
S	1.6	4.3	**0.61** [0.34 to 0.74]	*P*<.001
SLD	1.9	5.2	**0.45** [0.13 to 0.65]	*P* =.005
LD	1.8	4.9	**0.53** [0.24 to 0.70]	*P* <.001
ILD	2.4	6.5	**0.72** [0.57 to 0.83]	*P* <.001
SLND	1.7	4.8	**0.47** [0.15 to 0.66]	*P* =.004
LND	1.7	4.7	**0.54** [0.1 to 0.62]	*P* =.005
ILND)	2.5	6.8	**0.65** [0.42 to 0.78]	*P* <.001
Mean of means 3 targets (S / ILD / ILND)	1.0	2.8	**0.70** [0.45 – 0.77]	*P* <.001
Global mean PRO-Reach score (7 targets)	1.2	3.2	**0.77** [0.62 to 0.85]	*P* <.001

Caption: *Absolute within-day reliability of the PRO-Reach per direction of movement and composite scores (Mean ± Standard Deviation in centimeters [cm]) for both the first and second evaluations of shoulder proprioception (E1 and E2); AJPS =active joint position sense, ICC = intraclass correlation coefficient, SEM = standard error of measurement, MDC95 = minimal detectable change at 95% confidence.*

PRO-Reach targets: Superior (S), Superior Lateral Dominant (SLD), Lateral Dominant (LD), Inferior Lateral Dominant (ILD), Superior Lateral Non-Dominant (SLND), Lateral Non-Dominant (LND) and Inferior Lateral Non-Dominant (ILND).

Effect of fatigue

The mean fatigue time was 10.0 (± 5.6) minutes with a BORG rating of 17.3 (± 1.2). Dependent *t* tests between the second evaluation (E2) and the post-fatigue evaluation (E3) revealed statistically significant fatigue effects over time with two targets in elevation only, the S target and the SLD target ($P < .05$) (Table 5).

Table 5 Descriptive statistics and dependent *t*-tests of the proprioception errors of the PRO-Reach in centimeters before (E2) and after (E3) a fatiguing protocol (n=20)

AJPS reaching movement	**E2**	**E3**	**Dependent *t*-test Mean difference ± SD [CI]**
S	2.9 ± 1.4 [1.1 – 5.8]	3.8 ± 1.5 [1.5 – 5.8]	*t* = -1.7 (19) *P* = .05* -.8 ± 2.3 [-1.9 – .02]
SLD	3.1 ± 1.1 [1.6 – 5.1]	3.9 ± 1.5 [1.4 – 7.2]	*t* = -2.1 (19) *P* = .025* -.8 ± 1.8 [-1.7 – .0]
LD	4.0 ±1.7 [1.1 – 7.0]	4.4 ± 2.6 [1.2 – 10.4]	*t* = -.8 (19) *P* = .22 -.4 ± 2.3 [-.5 – 1.5]
ILD	4.8 ± 3.0 [1.3 – 12.2]	4.5 ± 1.9 [1.9 – 9.9]	*t* = -.9 (19) *P* = .17 -.8 ± 3.8 [-2.6 – .9]
SLND	4.7 ± 2.4 [0.9 – 9.5]	4.8 ± 1.6 [1.4 – 7.2]	*t* = .01 (19) *P* = .44 .08 ± 2.2 [-.9 – 1.1]
LND	4.2 ± 2.2 [1.1 – 11.5]	4.4 ± 2.0 [1.6 – 8.9]	*t* = .01 (19) *P* = .49 .01 ± 3.3 [-1.5 – 1.6]
ILND	5.9 ± 3.0 [1.3 – 13.6]	5.5 ± 2.0 [1.8 – 9.9]	*t* = .4 (19) *P* = .34 .4 ± 3.8 [-1.4 – 2.1]
Global mean PRO-Reach score (7 targets)	4.0 ± 1.0 [2.5 – 5.9]	4.3 ± 0.9 [2.6 – 5.9]	*t* = -1.3 (19) *P* = .09 -3.8 ± 1.3 [-.3 – .9]

Caption: *AJPS = active joint position sense.*

Descriptive statistics (Proprioception Errors [PE] in centimeters [cm]) of healthy participants (n=20) for the analysis of a post-fatigue effect. Mean difference between E2 and E3 ± SD [Confidence Intervals] of the PE.

E2 – second evaluation 60-minutes later, E3 – final evaluation following a muscular fatigue protocol (n=20). (*) indicate statistically significant results.

PRO-Reach targets: Superior (S), Superior Lateral Dominant (SLD), Lateral Dominant (LD), Inferior Lateral Dominant (ILD), Superior Lateral Non-Dominant (SLND), Lateral Non-Dominant (LND) and Inferior Lateral Non-Dominant (ILND).

DISCUSSION

The purpose of this study was to present the development and initial validation of a new tool, the PRO-Reach, with the aim of exploring its potential for measuring upper limb active joint position sense in a clinical setting. Our reasoning behind the evaluation of an unconstrained upper limb reaching movement, was to simulate daily function so as to maximize the tool's ecological validity, or resemblance to real life [40].

Our most important findings include the strongest intra-rater within-day reliability properties with the lower range targets for both ipsi-lateral and contra-lateral (cross-body) reaching movements (ICC = 0.72 and ICC = 0.65 for the ILD and ILND targets). Moreover, a good overall level of within-day reliability of the PRO-Reach (all seven targets, ICC = 0.77) was established. Our reliability findings are in agreement with other clinically based tools for the measurement of upper limb AJPS.

The reliability properties of the PRO-Reach decreased with reaching movements in elevation (ICC = 0.45 to 0.58). As the elevation of the movements increase, so does the possibility of a greater combination of degrees of freedom for all upper limb joints [57] and trunk [58]; and arguably, so does the variability of the movement strategies used by each participant [59]. This is reflected within our findings through the larger MDC and ICC values. Our findings are contrary to other studies using proprioception outcomes in elevation, which report a better proprioception acuity with elevated movements [59, 60]. A kinematic study looking at the effects

of body positioning on shoulder proprioception, found that the orientation of the body, and consequently the gravitational torque of the GH joint, did have an impact on PEs. They found that PEs in the supine condition increased from 70° to 110°, while they decreased across elevations while upright [60]. This is interesting to consider for the PRO-Reach, as movement strategies such as a trunk lean, were not corrected during the evaluations. This could also explain why the reliability measures were better with the inferior targets (ICCs > 0.7), as participants could have chosen more upper limb movement, and less of a trunk lean. The inferior targets also required less of a reaching trajectory overall, as the targets were closer in distance (shorter reaches) compared to the elevated targets (longer reaches). Closer targets could mean less opportunity for varied movements strategies, and a more reliable sense of proprioception.

The PRO-Reach was not able to detect a post-shoulder fatigue decline in AJPS, a well-documented alteration [1]. A fatigue effect was only noted with the elevated reaching movements with the PRO-Reach (S and SLD). It is possible that other upper limb joints compensated for the shoulder AJPS decline caused by the fatigue protocol. Moreover, the use of the Borg Rating of Perceived Exertion scale may not have been the most appropriate outcome for measuring an individual's effort and exertion, as it is not specific to muscular fatigue [61]. A non-invasive method for quantifying muscle fatigue, such as electromyography, or a pre- and post-measurement of the maximum voluntary contraction (MVC) [62], could have eliminated the subjectivity of the protocol.

Our findings of fatigue in elevation are similar to those reported by Zanca and colleagues, who found a significant increase in the PEs pre and post muscle fatigue at higher target angles of elevation (70° and 90°, but not 50° of scaption) [20]. Caution should be applied when comparing these results to the PRO-Reach, as their evaluation of AJPS did not surpass shoulder height (90°), whereas as the PRO-Reach evaluated reaching movements in all directions and heights. Moreover, Zanca and colleagues used an app developed for Apple's 4th generation iPod Touch, as a digital inclinometer, with within-day and between-day ICCs ranging from 0.64 – 0.80 [20]; which is comparable to the current levels of reliability for measuring AJPS of the shoulder [22]. It remains unclear whether shoulder and upper limb AJPS improves (lower PEs) [63, 64] or worsens (higher PEs following a fatigue protocol) [20] with

elevated movements. The effects of fatigue of the entire limb, not limited to a localized shoulder fatigue on AJPS, warrants further investigation.

The current challenge with comparing AJPS reliability studies includes the vast differences in instrumentation and methods for calculating the PE. There has yet to be two studies which use the same tool, direction or amplitude of movement, study parameters, or population; all adding to the challenge of quantifying AJPS [65]. Vafadar and colleagues (2016) used clinical tools to quantify shoulder AJPS of three pre-determine forward flexion ranges (low range 55° ± 10°, midrange 90° ± 10°, and high range 125° ± 10°), and reported inter-day reliability (48-hours apart) values with an inclinometer (inter-rater ICC = 0.67, intra-rater ICC = 0.70), goniometer (inter-rater ICC = 0.60, intra-rater ICC = 0.60) and laser pointer (inter-rater ICC = 0.86, intra-rater ICC = 0.78) [23]. A recent study by Sutton and colleagues (2022) acknowledged Vafadar's AJPS evaluations to be efficient; however, they concluded that the calculation of the angle errors afterwards remained time-consuming for clinicians [30]. Sutton's solution was to employ a modified AJPS test using a laser pen and a calibrated two-dimensional (2D) target for swift and feasible calculation of PEs in real-time. Although Vafadar's (inter-rater ICC = 0.86, intra-rater ICC = 0.78) and Sutton's protocols (ICC = 0.78) supports a similar reliability level compared to the PRO-Reach (ICC = 0.77); their methods evaluated the GH joint in a single plane of movement only. This arguably supports less ecological validity, as multiple planes of movement involving the entire upper limb more closely resembles daily movements patterns, as evaluated using the PRO-Reach.

Our results also suggest that upper limb reaching movements, as performed with the PRO-Reach, could be clinically feasible for a functional assessment of upper limb AJPS. Depending on the time available for assessment, one target (less than 5-minutes), three targets (12-15 minutes) or the entire PRO-Reach (seven targets, 25-30 minutes) could be achievable for a clinician to measure upper limb AJPS over time.

Future Research

Issues that remain to be resolved concerning upper limb AJPS include psychometrically tested outcome measures with pathological populations, which would advance our understanding of suspected proprioception deficits amongst individuals experiencing upper limb MDs and pain. Scientific trends suggest that different sub-modalities of proprioception are affected differently by different pathologies [66]; we therefore advocate for the use of the PRO-Reach with different populations.

As this is a newly developed AJPS outcome measure, the methodological testing of this tool is still within its infancy. The continued psychometric testing of the PRO-Reach will include the establishment of known-group validity, between pathological and healthy populations, evaluating between-day and inter-rater reliability properties, as well as determining normative data and responsiveness measures for clinical application. This includes the further investigation of between-day minimal detectable change (MDC) and the minimum clinically important difference (MCID) values for each target and the global mean PRO-Reach score.

Strengths and limitations of the study

The PRO-Reach is a user-friendly tool which employs functional and active reaching movements for the assessment of upper limb AJPS. It has potential for use in a clinical setting for practitioners who are interested in the assessment and progression of proprioception in their treatment strategy.

Nonetheless, there are limitations which should be addressed for future research. Our study involved a newly developed tool and we chose to work with healthy participants. The evaluation of a healthy population could have caused a lack of variability in our data and consequently could have impacted our reliability and discriminant validity measures; more specifically our absolute reliability measures of SEM and MDCs and a lack of a significant post-fatigue effect. Moreover, given the high MDC values, it is currently more difficult to acknowledge a difference between two values as a real difference, and not only a result of measurement errors. Large MDCs may also reflect the known large variability and difficulty in measuring proprioception deficits itself [26]. In addition, the inter-rater and inter-day reliability needs to be established for the PRO-Reach. It would also be interesting to evaluate

the methodological qualities of this tool in different positions, sitting versus standing, for example.

CONCLUSIONS

Our intra-rater within-day study revealed moderate reliability of the PRO-Reach (overall mean, ICC = 0.77) for quantifying upper limb AJPS with an active reaching movement; which is in line with the reported psychometric properties of upper limb proprioception outcome measures at present. The shoulder fatigue protocol did influence proprioception acuity in elevation, but not with the PRO-Reach as a whole. Given the simplicity of this tool, the efficient evaluation method and an appreciable level of reliability for this first phase of development of the PRO-Reach, this tool could have clinical merit. Our initial results made it possible to identify potential solutions for quantifying upper limb AJPS which will guide further refinement of this novel outcome measure. It is our aim to continue the development of tool, which could easily be integrated into clinical practice.

DECLARATIONS

Ethics approval and consent to participate

Ethical approval was provided by the Ethical Committee of Ghent University on 25/05/2018, with a Belgian Registration Number of B670201836235 and the Ethics and Research Committee of the *Institut de réadaptation en déficience physique de Québec* (IRDPQ), ethics case numbers 2015-426 and 2015-446. All participants gave and written consent to partake in this study. All methods were performed in accordance with the relevant guidelines and regulations as outlined by the Declaration of Helsinki (1964).

Consent for publication

All authors give full and informed consent for publication.

Availability of data materials

All authors consent to all data being openly public and accessible.

Competing interests

There are no competing interests to declare. No conflict of interest exists from any of the authors involved in this paper.

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Author contributions

All named authors have made a significant and substantial contribution to all aspects of the study. Each of the named authors provided a meaningful contribution to the conception, design, execution and interpretation of the study data in addition to writing, drafting and revising the paper itself. This paper is submitted with the agreement and approval of all authors.

List of Figures, Tables & Supplementary Appendices

REFERENCES

Uncategorized References

1. Proske U. Exercise, fatigue and proprioception: a restrospective. *Exp Brain Res.* 2019;237(10).
2. Ager AL, Borms, D., Deschepper, L., Dhooghe, R., Dijkhuis, J., Roy, J.S., & Cools, A. Proprioception: how is it affected by shoulder pain? A systematic review. . *Journal of hand therapy : official journal of the American Society of Hand Therapists.* 2019;In press.
3. Röijezon U, Clark, N.C., & Treleaven, J. Proprioception in musculoskeletal rehabilitation Part 1: Basic science and principles of assessment and clinical interventions. *Man Ther.* 2015;20(3):368-377.
4. Lephart SM, Fu FH. *Proprioception and neuromuscular control in joint stability*. [Champaign, IL]: Human Kinetics; 2000.
5. Clark NC, Roijezon, U., & Treleaven, J. . Proprioception in musculoskeletal rehabilitation. Part 2: Clinical assessment and intervention. . *Manual Therapy.* 2015;20:378-387.
6. Albanese GA MF, Morasso P, Campus C, Zenzeri J. μ-band desynchronization in the contralateral central and central-parietal areas predicts proprioceptive acuity. . *Front Hum Neurosci.* 2023;17.
7. Ingram HA, van Donkelaar, P., Cole, J., Vercher, J-L., Gauthier, G.M., & Miall, R.C. The role of proprioception and attention in a visuomotor adaptation task. *Exp Brain Res.* 2000;132:114-126.
8. Kuczynski AM KA, Semrau JA, Dukelow SP. Relative independence of upper limb position sense and reaching in children with hemiparetic perinatal stroke. *J Neuroeng Rehabil.* 2021;18(1).
9. Knox J, Beilstein, D., Charles, S.D., Aarseth, G.A., Rayar, S., Treleaven, J., & Hodges, P.W. Changes in head and neck position have greater effect on elbow joint position sense in people with whiplash-associated disorders. *Clin J Pain.* 2006;22(6):512-518.
10. Safran M, Borsa, P., Lephart, F., Fu,F., Warner, J., & Arbor, A. Shoulder proprioception in baseball pitchers. *Journal of shoulder and elbow surgery / American Shoulder and Elbow Surgeons [et al].* 2001;10(5):438-444.
11. Barden JM, Balyk, R., Raso, V.J., Moreau, M., & Bagnal, K. Dynamic upper limb proprioception in multidirectional shoulder instability. *Clin Orthop Relat Res.* 2004;420:181-189.
12. Lephart SM, Warner, J.J.P., Borsa, P.A., & Fu, F.H. . Proprioception of the shoulder joint in healthy, unstable, and surgically repaired shoulders. . *J Shoulder Elbow Surg.* 1994;3(6):371-381.
13. Zuckerman J, Gallagher, M., Cuomo, F., & Rokito, A. The effect of instability and subsequent anterior shoulder repair on proprioceptive ability. . *Journal of shoulder and elbow surgery / American Shoulder and Elbow Surgeons [et al].* 2003;12(2):105-109.
14. Cuomo F, Birdzell, M.G., & Zuckerman, J.D. The effect of degenerative arthritis and prosthetic arthroplasty on shoulder proprioception. *Journal of shoulder and elbow surgery / American Shoulder and Elbow Surgeons [et al].* 2005;14(4):345-348.

15. Ludewig PM, & Cook, T.M. Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. *Phys Ther.* 2000;80(3):276-291.
16. Reddy AS, Mohr Ramsey, J., & Riddoch, M. Position-matching in the upper limb; professional ballet dancers perform with outstanding accuracy. *Clinical rehabilitation.* 2001;15(3):324-330.
17. Machner A, Merk, H., Becker, R., Rohkohl, K., Wissel, H., & Pap, G. Kinesthetic sense of the shoulder in patients with impingement syndrome. *Acta Orthop Scand.* 2003;74(1):85-88.
18. Gumina S, Camerota, F., Celletti, C., Venditto, T., & Candela, V. The effects of rotator cuff tear on shoulder proprioception. *Int Orthop.* 2019;43(1):229-235.
19. Walecka J, Lubiatowski, P., Consigliere, P., Atoun, E., & Levy, O. . Shoulder proprioception following reverse total shoulder arthroplasty. *International Orthopaedics.* 2020;44(12):2691-2699.
20. Zanca GG, Mattiello SM, Karduna AR. Kinesio taping of the deltoid does not reduce fatigue induced deficits in shoulder joint position sense. *Clin Biomech (Bristol, Avon).* Nov 2015;30(9):903-907.
21. Ager AL, Borms, D., Bernaert, M., Brusselle, V., Claessens, M., Roy, J-S., & Cools, A. . Can a conservative rehabilitation strategy improve shoulder proprioception? A systematic review. *Journal of Sport Rehabilitation* 2021;30:136-151.
22. Ager AL, Roy, J.S., Roos, M., Belley, A.F., Cools, A., & Hebert, L.J. Shoulder proprioception: How is it measured and is it reliable? A systematic review. *J Hand Ther.* 2017;30(2):221-231.
23. Vafadar AK, Côté, J.N., & Archambault, P.S. . Inter-rater and Intra-rater reliability and validity of three measurement methods for shoulder position sense. . *Journal of Sport Rehabilitation Technical Report.* 2015(19):2014-0309.
24. Hillier S, Immink, M., & Thewlis, D. Assessing Proprioception: A Systematic Review of Possibilities. *Neurorehabil Neural Repair.* 2015;29(10):933-949.
25. Elangovan N, Hermann, A., & Konczak, J. Assessing proprioceptive function: evaluating joint position matching methods against psychophysical thresholds. *Phys Ther.* 2014;94(4):553-561.
26. Han J, Waddington, G., Adams, R., Anson, J., & Liu Y. . Assessing proprioception: a critical review of methods. . *Journal of Sport and Health Science.* 2016;5(1):80-90.
27. Fyrh C, Gustavsson, L., Wassinger, C., & Sole, G. . The effect of shoulder injury on kinesthesia: A systematic review and meta-analysis. . *Manual Therapy.* 2015(20):28-37.
28. SH. S. The computational and neural basis of voluntary motor control and planning. *Trends Cogn Sci.* 2012;16:541-549.
29. Limanowski J BF. Integration of Visual and Proprioceptive Limb Position Information in Human Posterior Parietal, Premotor, and Extrastriate Cortex. *J Neurosci.* 2016;36(9):2582-2589.
30. Sutton P LOM, & Röijezon U. . Reduced shoulder proprioception due to fatigue after repeated handball throws and evaluation of test–retest reliability of a clinical shoulder joint position test. *Shoulder & elbow.* 2022;0(0).

31. Ramsay JRE, & Riddoch, M.J. . Position-matching in the upper limb: professional ballet dancers perform with outstanding accurary. *Clinical Rehabilitation* 2001;15:324-330.
32. Dover G, & Powers, M.E. . Reliability of joint position sense and force-reproduction measures during internal and external rotation of the shoulder. . *Journal of Athletic Training.* 2003;38(4):304-310.
33. Başkurt Z, Başkurt, F., Gelecek, N., & Özkan, M.H. The effectiveness of scapular stabilization exercise in the patients with subacromial impingement syndrome. *Journal of Back and Musculoskeletal Rehabilitation.* 2011;24(3):173-179.
34. Burfeind SMC, N. Randomized control trial investigating the effect of kinesiology tape on shoulder proprioception. *Journal of sport rehabilitation.* 2015;24:405-412.
35. de Oliveira FCL, de Fontenay, B.P., Bouyer, L.J., & Roy, J.S. Immediate effects of kinesiotaping on acromiohumeral distance and shoulder proprioception in individuals with symptomatic rotator cuff tendinopathy. *Clinical Biomechanics.* 2019;61(16-21.).
36. Herrington L, Horsley, I., Whitaker, L., & Rolf, C. . Does a tackling task effect shoulder joint position sense in rugby players. . *Physical Therapy Sport.* 2008;9:67-71.
37. Morgan R, & Herrington, L. The effect of tackling on shoulder joint positioning sense in semi-professional rugby players. *Physical Therapy Sport.* 2014;15:176-180.
38. Burfeind SM, Chimera N. Randomized Control Trial Investigating the Effects of Kinesiology Tape on Shoulder Proprioception. *Journal of sport rehabilitation.* Nov 2015;24(4):405-412.
39. Han J WG, Adams R, Anson J, & Liu Y. Assessing proprioception: What do you really want to know?-Response to Krewer et al. *J Sport Health Sci.* 2016;5(1):93-94. .
40. Gibson JJ. *The ecological approach to visual perception.* Hillsdale, NJ: Erlbaum; 1979.
41. Han J, Waddington, G., Anson, J., & Adams, R. Level of competitive success achieved by elite athletes and multi-joint proprioceptive ability. *J Sci Med Sport.* 2015;18(1):77-81.
42. Koo TK, & Li, M.Y. A guideline of selecting and reporting Intraclass Correlation Coefficients for reliability research. *J Chiropr Med.* 2016;15(2):155-163. .
43. Ribeiro F, & Oliveira, J. *Chapter 14: Factors Influencing Proprioception: What do they reveal?*: InTech.; 2011.
44. Proske UG, S.C. The proprioceptive senses: their roles in signaling body shape,body position and movement, and muscle force. *Physiol Rev.* 2012;92:1651-1697.
45. A B. Bases neurales de l'orientation spatiale et de la mémoire des trajets: mémoire topo-graphique ou mémoire topo-kinesthésique? [Neural basis of spatial orientation and memory of routes: topokinetic memory or topokinesthesic memory]. *Rev Neurol (Paris).* 2001;157:779-789.
46. Kennedy CA BD, Solway S, McConnell S, Bombardier C. . *Disabilities of the Arm, Shoulder and Hand (DASH). The DASH and QuickDASH Outcome Measure User's Manual*. Third Edition ed. Toronto, Ontario; 2011.

47. Ransil BJ, & Schachter, S.C. Test-retest reliability of the Edinburgh Handedness Inventory and Global Handedness preference measurements, and their correlation. *Percept Mot Skills.* 1994;79(3 Pt 1):1355-1372.
48. Franchignoni F VS, Giordano A, Sartorio F, Bravini E, Ferriero G. Minimal clinically important difference of the disabilities of the arm, shoulder and hand outcome measure (DASH) and its shortened version (QuickDASH). *J Orthop Sports Phys Ther* 2014;44(1):30-39.
49. Gummesson C, Ward, M.M. & Atroshi, I. The shortened disabilities of the arm, shoulder and hand questionnaire (Quick DASH): validity and reliability based on responses within the full-length DASH. *BMC Musculoskelet Disord.* 2006;7(44).
50. Haahr M. Random.org.
51. Ebaugh DD, McClure, P.W., & Karduna, A.R. Effects of shoulder muscle fatigue caused by repetitive overhead activities on scapulothoracic and glenohumeral kinematics. *J Electromyogr Kinesiol.* 2006;16(3):224-235.
52. Hébert LJ. *Évaluation de la force musculaire et dynamomètres manuels : Concepts de base et applications pratiques*. 3e éd. ed. ed: INVENTUM, Bibliothèque nationale du Québec et Bibliothèque et Archives Canada; 2012.
53. Legally KM, & Amorose, A.J. . The validity of using prior ratings of perceived exertion to regulate resistance exercise intensity. *Percept Mot Skills.* 2007;104(2):534-542. .
54. Terwee CB, Mokkink, L.B., Knol, D.L., Ostelo, R.W.J.G., Bouter, L.M., & de Vet, H.C.W. . Rating the methodological quality in systematic reviews of studies on measurement properties: a scoring system for the COSMIN checklist. . *Qual Life Res* 2012(21):651-657.
55. de Vet HC, Terwee, C.B., Knol, D.L., Bouter, L.M. When to use agreement versus reliability measures. *J Clin Epidemiol.* 2006;59(10):1033-1039.
56. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J Strength Cond Res.* 2005;19(1):231-240.
57. Gates DH WL, Cowley J, Wilken JM, & Resnik L. Range of Motion Requirements for Upper-Limb Activities of Daily Living. *Am J Occup Ther.* 2016;70(1):7001350010p7001350011-7001350010p7001350010.
58. Tomita Y FA, & Levin MF. Referent control and motor equivalence of reaching from standing. *J Neurophysiol.* 2016;117(1):303-315. .
59. Diefenbach BJ, & Lipps, D.B. Quantifying the three-dimensional joint position sense of the shoulder. *Hum Mov Sci.* 2019;67.
60. Suprak DN SJ, Chalmers GR, Cunningham W. . Shoulder elevation affects joint position sense and muscle activation differently in upright and supine body orientations. *Hum Mov Sci* 2016;46:148-158.
61. Williams N. The Borg Rating of Perceived Exertion (RPE) scale. *Occupational Medicine.* 2017;67(5):404-405.
62. Al-Mulla MR SF, Colley M. A Review of Non-Invasive Techniques to Detect and Predict Localised Muscle Fatigue. *Sensors.* 2011;11(4):3545-3594.
63. Suprak DN, Osternig LR, van Donkelaar P, Karduna AR. Shoulder joint position sense improves with elevation angle in a novel, unconstrained task. *Journal of orthopaedic research : official publication of the Orthopaedic Research Society.* Mar 2006;24(3):559-568.

64. Chapman J SD, & Karduna AR. Unconstrained shoulder joint position sense does not change with body orientation. *J Orthop Res.* 2009;27(7):885-890.
65. Elangovan N, Herrmann A, Konczak J. Assessing proprioceptive function: evaluating joint position matching methods against psychophysical thresholds. *Phys Ther.* Apr 2014;94(4):553-561.
66. Phillips D, & Karduna, A. No relationship between joint position sense and force sense at the shoulder. *Journal of Motor Behavior.* 2017;50(2):228-234.