VU Research Portal

Description and psychometric properties of a prototype to test tactile acuity in the neck

Olthof, Nick A.; Harvie, Daniel S.; Henderson, Courtney; Thompson, Brendan; Sharp, Robert; Craig-Ward, Lauren; Weermeijer, Jeroen D.; Sterling, Michele; Moseley, G. Lorimer; Coppieters, Michel W.

published in

Musculoskeletal Science and Practice
2021

DOI (link to publisher)

[10.1016/j.msksp.2020.102259](https://doi.org/10.1016/j.msksp.2020.102259)

document version

Publisher's PDF, also known as Version of record

document license

Article 25fa Dutch Copyright Act

[Link to publication in VU Research Portal](#)

citation for published version (APA)

Olthof, N. A., Harvie, D. S., Henderson, C., Thompson, B., Sharp, R., Craig-Ward, L., Weermeijer, J. D., Sterling, M., Moseley, G. L., & Coppieters, M. W. (2021). Description and psychometric properties of a prototype to test tactile acuity in the neck. *Musculoskeletal Science and Practice*, 51, 1-6. [102259].
<https://doi.org/10.1016/j.msksp.2020.102259>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

E-mail address:

vuresearchportal.ub@vu.nl

Technical and measurement report

Description and psychometric properties of a prototype to test tactile acuity in the neck

Nick A. Olthof^{a,b}, Daniel S. Harvie^{a,b,*}, Courtney Henderson^a, Brendan Thompson^a, Robert Sharp^a, Lauren Craig-Ward^a, Jeroen D. Weermeijer^c, Michele Sterling^{d,e}, G. Lorimer Moseley^f, Michel W. Coppieters^{b,g}

^a School of Allied Health Sciences, Griffith University, Brisbane and Gold Coast, Australia

^b Menzies Health Institute Queensland, Griffith University, Brisbane and Gold Coast, Australia

^c Center for Contextual Psychiatry, Katholieke Universiteit Leuven, Leuven, Belgium

^d RECOVER Injury Research Centre, The University of Queensland, Brisbane, Australia

^e NHMRC Centre of Research Excellence in Road Traffic Injury Recovery, The University of Queensland, Brisbane, Australia

^f IIMPACT in Health, University of South Australia, Adelaide, Australia

^g Amsterdam Movement Sciences, Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands

ARTICLE INFO

Keywords:

Touch perception (MeSH)
Tactile acuity
Reliability (MeSH)
Validity (MeSH)
Neck (MeSH)
Chronic pain (MeSH)

ABSTRACT

Background: Clinical tools assessing tactile acuity in people with persistent pain have limitations. Therefore, a novel and semi-automated tool was developed: The Imprint Tactile Acuity Device (iTAD).

Aim: To describe the iTAD prototype and present the psychometric properties of its tactile acuity assessments: the localisation test, the orientation test and the overall score (mean of both tests).

Method: A test-retest design with fifty healthy participants was used to assess intra-rater reliability ($ICC_{(2,1)}$), internal consistency ($ICC_{(2,4)}$) and measurement error (SEM) of the three assessments (0–100% accuracy scores each) performed at the neck. Using a known-group comparison design, balanced by age and sex, scores of thirty individuals with persistent neck pain were compared to thirty healthy controls to determine construct validity. **Results:** The $ICC_{(2,1)}$ and $ICC_{(2,4)}$ were 0.60 and 0.78 for the localisation test, 0.66 and 0.77 for the orientation test, and 0.73 and 0.84 for the overall score. The SEMs were 9.0%, 8.1% and 6.0%, respectively. No fixed or proportional bias, or signs of heteroscedasticity were observed. Overall, no between group differences were observed ($p = 0.49$). In the male subgroup, however, the overall score was lower for people with neck pain than for healthy participants (mean difference (SE); 7.6% (2.5); $p = 0.008$).

Discussion: The tactile acuity assessments of the iTAD demonstrate moderate reliability and good internal consistency. Measurement errors appear comparable to currently preferred methods. Clear construct validity was not established, but results may be biased by design issues of the prototype. Taken together, the iTAD shows promise but further fine-tuning is needed.

1. Background

Impaired tactile acuity has been observed in several persistent pain conditions (Catley et al., 2014). The degree of impairment has been related to both pain intensity and changes in cortical responses to tactile input (Flor et al., 2001; Pleger et al., 2001, 2006). Several studies implicate the primary sensory cortices as a possible site of reorganisation (Henry et al., 2011; Di Pietro et al., 2013), although recent studies suggest the neurological underpinnings of these tactile impairments are

likely to be more complex (Makin et al., 2015; Kuroki et al., 2017; Mancini et al., 2019). Despite this, the potential clinical utility of tactile acuity testing and training remains (Pleger et al., 2005; Moseley et al., 2008; Wand et al., 2013a).

Tactile acuity refers to the accuracy and clearness of touch perception and its assessment often involves determining the two-point discrimination threshold (TPDT) (Harvie et al., 2017). However, large measurement error has been observed in TPDT assessment (Catley et al., 2013), impeding its ability to identify treatment effects. Additionally, its

* Corresponding author. Menzies Health Institute Queensland, Griffith University, Parklands Drive, 4222, Southport, Australia
E-mail address: d.harvie@griffith.edu.au (D.S. Harvie).

<https://doi.org/10.1016/j.msksp.2020.102259>

Received 15 January 2020; Received in revised form 8 September 2020; Accepted 11 September 2020

Available online 14 September 2020

2468-7812/© 2020 Published by Elsevier Ltd.

validity has been questioned (Craig and Johnson, 2000) hindering interpretation of the scores. We developed a new device to improve the clinical assessment of tactile acuity at the neck, given the need for more research in this area (Luedtke and Adamczyk, 2017). The ‘imprint Tactile Acuity Device’ (iTAD) is a semi-automated tool that may be less affected by variance introduced by the tester, potentially reducing measurement error. Additionally, the iTAD assesses distinct aspects of tactile acuity: localisation and orientation discrimination. This Technical Note aims to: 1) describe the prototype of the iTAD, and 2) present the intra-rater reliability, measurement error, internal consistency and construct validity of its tactile acuity assessments.

2. Apparatus; the imprint Tactile Acuity Device (iTAD)

2.1. Hardware and software

The iTAD (see Fig. 1A and B) consists of a neoprene collar which is fitted around the neck. Twelve hemispherical plastic nodes, containing vibrotactile stimulators, contact the dorsum of the neck. Installed on an Android™ tablet, a custom-written application operates the vibrotactile stimulators wirelessly, records the user's responses and calculates accuracy scores. For a detailed description, see Fig. 1.

Fig. 1. **Panel A:** The prototype of the imprint Tactile Acuity Device (iTAD), consisting of a wearable neoprene collar (1 mm of neoprene lined back and front with lycra fabric), containing 12 vibrating nodes (1). The nodes are organised in 3 rows and 2 columns for each side of the neck. Centre-to-centre, the nodes are 45 mm (rows and middle columns) or 32.5 mm apart (outer columns) apart. Each node contains a vibrotactile stimulator (10.0 mm × 3.4 mm, shaftless eccentric rotating mass vibration motor (~220 Hz with 0.75 g vibration amplitude; www.pololu.com)). Each stimulator connects, via insulated wires, to a custom-printed circuit board with programmable Arduino microchip, sitting in a 3D printed (polyamide) enclosure (2), powered by a rechargeable lithium ion battery. The Android application is written in JAVA script using the Android software development kit, while the microcontroller runs on an Arduino ATmega328P chip flashed with Arduino code. The device has been classified as a Class 1 device under Australian Regulatory Guidelines for Medical Devices (ARGMD) and did not require approval by the Therapeutic Goods Administration. However, extensive electrical and thermal testing has been performed to provide safety for human usage. **Panel B:** The iTAD is secured around the neck (3) using the Velcro tags at the end of the collar's arms (4). The iTAD is wirelessly connected, via a Bluetooth connection, to a Lenovo TAB3 Android tablet with a 7-inch display and a 1.3 GHz CPU (5) running custom iTAD software to operate the device, collect the user's responses, and calculate accuracy scores. **Panel C:** The user interface displayed on the tablet during the familiarisation protocol and the localisation test, with each circle representing one of the 12 nodes. The user indicates the perceived location of the vibration by selecting the corresponding circle. **Panel D:** The user interface during the orientation test. The user indicates the perceived orientation of a second vibration, relative to a first, by selecting the corresponding arrow.

2.2. Fitting and familiarisation

The collar is applied comfortably but reasonably firm to ensure even contact across all nodes. The device is centred over the cervical spine with the user sitting in an upright position. For familiarisation, each node vibrates once with simultaneous location feedback on the tablet (see Fig. 1C).

2.3. The localisation test

The localisation test aims to measure accuracy in localising vibrotactile stimuli. During this test, a node vibrates for 1 s, after which the user indicates its perceived location by selecting the corresponding circle on the tablet (see Fig. 1C). One second after selection, another node vibrates until all twelve nodes have vibrated in a random order. The total test consists of four series of twelve vibrations. The test takes approximately 3 min to complete.

2.4. The orientation test

The orientation test aims to measure accuracy in determining the relative orientation of two successive stimuli. During this test, two adjacent nodes (not crossing the body midline) vibrate consecutively for 1 s each. The participant indicates the perceived orientation of the second vibration relative to the first by selecting the corresponding arrow on the tablet (see Fig. 1D). In one series, the eight possible orientations are offered in random order on both sides of the neck, resulting in 16 paired vibrations. The test consists of three series and takes approximately 4 min to complete.

2.5. Scoring

For the localisation and orientation tests, the application generates separate percentage correct scores (0–100%) with higher scores representing better accuracy. The ‘overall score’ is the mean of both scores.

3. Methods

A reliability and validity study were performed. All participants gave written informed consent prior to participating.

3.1. Reliability of the iTAD

A test-retest study assessed the intra-rater reliability, measurement error and internal consistency of the iTAD scores (Mokkink et al., 2010). Individuals without current pain or a history of persistent (i.e., >3 months) back, neck or arm pain, or headache were recruited among staff and students from university campus.

Following fitting and familiarisation, the localisation and orientation tests were performed consecutively in a quiet room. After a 15-min break, while the iTAD was removed, both tests were repeated by the same tester in the same order. Four physiotherapy students, who received approximately 1 h of training, performed the tests. Test instructions and performance were standardised. Participant and testers were blinded to the scores.

Intra-rater reliability was assessed by calculating the intraclass correlation coefficient model 2,1 (ICC_(2,1)) (i.e., two-way random, absolute agreement, single measures) (Koo and Li, 2016).

To assess measurement error, standard error of measurement (SEM) was calculated using variance components from the ANOVA table ($\sqrt{(\sigma^2_{\text{observer}} + \sigma^2_{\text{residual}})}$) (de Vet et al., 2006; McGraw and Wong, 1996). To aid clinical interpretation of the SEM, the 95% confidence interval of the true score ($1.96 \times \text{SEM}$) and the smallest detectable change (SDC) ($1.96 \times \sqrt{2} \times \text{SEM}$) were calculated (Weir, 2005). Additionally, coefficient of variation (CoV), i.e., SEM as a percentage of mean score, was calculated to aid comparison to other metrics (Hopkins, 2000). Bland and

Altman plots were charted to visually inspect (limits of) agreement (Giavarina, 2015). Fixed bias was assessed using a one-sample *t*-test to determine if the mean difference between repeated tests deviated from zero (Giavarina, 2015). Proportional bias was assessed using a linear regression to determine the relationship between the mean and the difference of repeated test scores (Giavarina, 2015).

To assess internal consistency, the 48 trials were divided in blocks of twelve for each test. Absolute agreement between the four blocks within each test were calculated using an ICC_(2,4) (i.e., two-way random, absolute agreement, average measure) (McGraw and Wong, 1996).

3.2. Construct validity of the iTAD

Construct validity was assessed using a known-group comparison design to test the hypothesis that patients with persistent neck pain would score lower than healthy participants (Harvie et al., 2018). Patients were recruited through advertisement in primary care clinics and among the general public. Patients needed to have neck pain (pain intensity ≥ 3 on a 0–10 pain rating scale) for >3 months. Patients could have referred arm pain, but not radiating in a dermatomal distribution. Patients with known neurological conditions were excluded, as well as patients reporting numbness, paraesthesia or motor deficits. Patients with a history of neck or shoulder surgery, neck or shoulder fractures, known mental health disorders or cancer were also excluded. In order to balance groups, healthy asymptomatic participants (no current pain or history of persistent back, neck or arm pain, or headache) were selected by matching their age (± 5 years) and sex.

The procedures were identical to the reliability study, with the exception that the tests were performed only once and by different examiners.

A one-way MANCOVA was used to compare groups for the localisation, orientation and overall scores, while adjusting for age. Age was entered as a covariate, because despite selecting controls of similar age, participants were not analysed as matched pairs (Miller and Chapman, 2001; Pearce, 2016). Planned secondary analyses assessed gender specific group differences. Post-hoc analyses were performed using independent sample *t*-tests. Effect sizes are reported in partial eta squared (η_p^2) or Cohen's *d* (*d*). Sample size calculation indicated that 60 participants were needed to find medium to large ($f^2 = 0.2$) differences in the primary analysis with alpha at 5% and 80% power.

4. Results

4.1. Reliability of the iTAD

Fifty adults (25 females, mean (SD) age: 37.7 (17.5) years) participated. Mean (SD) accuracy scores, averaged between repeated tests, were 63.9% (12.7) for the localisation test, 53.5% (12.5) for the orientation test and 58.7% (10.9) for the overall score.

Mean ICC_(2,1) values for intra-rater reliability were 0.60 (localisation test), 0.66 (orientation test) and 0.73 (overall score) (see Table 1).

Results showed a SEM of 9.0% for the localisation test, 8.1% for the

orientation test and 6.0% for the overall score (see Table 1). The 95% confidence interval of the true score, SDC and CoV, are also summarised in Table 1. Bland and Altman plots are displayed in Fig. 2. No score had a significant fixed ($p \geq 0.41$) or proportional bias ($p \geq 0.26$). Visual inspection of the residual plot revealed no signs of heteroscedasticity.

Averaged between the two repeated tests, the mean ICC_(2,4) values for internal consistency were 0.78 for the localisation test, 0.77 for the orientation test, and 0.84 for the overall score (see Table 1).

4.2. Construct validity of the iTAD

Thirty adults with persistent neck pain and thirty healthy volunteers participated in the study. Participant characteristics are summarised in Table 2.

Most distributions were left skewed but were normalised following squared transformation. There was no significant between group difference for the total sample ($F(3, 55) = 0.812, p = 0.49, \eta_p^2 = 0.04$) (see Fig. 3). Secondary analyses showed a large ($\eta_p^2 > 0.13$) significant between group difference in men ($n = 28$), $F(3, 23) = 3.372, p = 0.04, \eta_p^2 = 0.31$, indicating that group difference explained 31% of the variance in tactile acuity after adjusting for age. Among women ($n = 32$), group differences were not significant: $F(3, 27) = 0.456, p = 0.72, \eta_p^2 = 0.05$. Post-hoc analyses in the male subgroup indicated no significant difference between groups for the localisation ($d = 0.63; p = 0.11$) or orientation ($d = 0.63; p = 0.10$) test, but there was a large ($d > 0.8$) significant difference for the overall score ($d = 1.13; p = 0.008$), with the patients scoring on average (SE) 7.6% (2.5%) lower than healthy participants (see Fig. 3).

5. Discussion

Results show moderate (Portney and Watkins, 2009) intra-rater reliability for the iTAD's three tactile acuity assessments. Compared to the ICC values for the TPDT assessment, the ICC value for the iTAD's overall score was similar, while the ICC values of the individual tests were slightly lower (Harvie et al., 2017; Catley et al., 2013; Luedtke et al., 2018). However, ICC values can be inflated by large between subject variance, even where large measurement error is present (Bartlett and Frost, 2008). Indeed, some studies have observed large between-subject variance in TPDT assessment (Catley et al., 2013), and so comparing the reliability of these methods on ICC values alone may not be appropriate.

Unlike ICC values, measures of measurement error (i.e., SEM) are not influenced by between-subject variance, but there are no standardised cut-offs for interpretation. However, the CoV can be used to contrast measurement tools and the CoV of the iTAD assessments are comparable with those of the TPDT (10.5% (Harvie et al., 2017), 11.6% (Luedtke et al., 2018) and 19.1% (Catley et al., 2013)). The large SDCs (25.0% and 22.3%), however, suggest that independent iTAD tests of this prototype should not yet be used clinically, although the SDC of the overall score appears acceptable (16.7%). Encouragingly, the lack of bias and heteroscedasticity indicate that reliability and measurement error

Table 1

Intra-rater reliability, measurement error and internal consistency the localisation test, orientation test and overall score.

	Intra-rater reliability	Measurement error					Internal consistency
	ICC _(2,1) (95% CI)	Mean difference (SD)	SEM	95% CI of true score	SDC	CoV	ICC _(2,4) (95% CI)
Localisation test	0.60 (0.38; 0.75)	0.8% (12.9)	9.0%	$\pm 17.7\%$	25.0%	14.1%	Test 1: 0.81 (0.71; 0.88) Test 2: 0.74 (0.60; 0.84)
Orientation test	0.66 (0.47; 0.79)	1.3% (11.4)	8.1%	$\pm 15.8\%$	22.3%	15.0%	Test 1: 0.78 (0.66; 0.87) Test 2: 0.76 (0.63; 0.85)
Overall score	0.73 (0.58; 0.84)	1.0% (8.6)	6.0%	$\pm 11.8\%$	16.7%	10.3%	Test 1: 0.84 (0.75; 0.90) Test 2: 0.84 (0.75; 0.90)

ICC: intraclass correlation coefficient; SEM: standard error of measurement; SDC: smallest detectable change; CoV: Coefficient of variation. Test 1 refers to the first test in the test-retest procedure. Test 2 refers to the second test.

Fig. 2. Bland and Altman limits of agreement for the localisation test (upper plot), the orientation test (middle plot) and the overall score (bottom plot) for the iTAD prototype. The middle line represents the mean difference between repeated tests. The top and bottom lines represent the upper and lower limits of agreement.

Table 2
Participant characteristics.

	Patient group (n = 30)	Healthy control group (n = 30)
Sex (n)	Female: 16 Male: 14	Female: 16 Male: 14
Age in years	50.9 (15.9)	49.9 (14.5)
Median (IQR) duration of symptoms in years	5.6 (12.9)	N/A
Pain intensity (NRS 0–10)		
- Current pain	4.1 (2.2)	N/A
- Average pain over past 2 weeks	4.5 (1.8)	N/A
- Highest pain over past 2 weeks	6.8 (2.5)	N/A
Disability (NDI)	15.5 (6.2)	N/A

IQR = interquartile range, NRS = Numeric Rating Scale, NDI = Neck Disability Index. Mean (SD) are reported, unless otherwise stated.

estimates are not dependent on the obtained score and the score does not appear to be influenced by repeated testing.

Internal consistencies for all three assessments were good (Taber, 2018), indicating relative within-test stability. This suggests between-test error might be a result of non-test factors, such as inconsistent device fitting, which might be overcome with design modification.

Some variance within and between repeated tests could also be due to true variability, a known feature of unstable variables, such as heart rate variability (Pinna et al., 2007) and reaction time (Saville et al., 2011). Sensory perceptions are known to be variable (Ribeiro et al., 2016), impeding reliability of its measures. Increasing the number of trials within each test could counter this predicament (Portney and Watkins, 2009).

Surprisingly, construct validity seemed low, given that between group differences only reached significance for the overall score in men. The lack of group differences could, however, be due to several reasons. First, although reliability and validity are separate properties, validity cannot be achieved when reliability is lacking (Kimberlin and Winterstein, 2008). Thus, establishing validity may depend on improving reliability. Second, the results could be biased by difficulties in fitting of the iTAD prototype. Six (all females) of the nine participants (all healthy controls) who reported difficulties with fitting due to slimmer and/or shorter necks, showed markedly low tactile acuity and were classified as outliers in untransformed data. Third, subgroup analyses had low statistical power due to small numbers, increasing the risk of type II error. Despite this, group differences were still found for the male subgroup, which reached significance for the overall score and approached significance for the individual tests with moderate sized ($d > 0.5$) mean (SE) differences of 6.4% (3.8) for the localisation test and 8.8% (5.3) for

the orientation test. Fourth, there appeared to be large between-subject variability, even in healthy participants, making group discrimination more difficult. Additionally, not all individuals with persistent pain will have reduced tactile acuity, which decreases group differences. Correspondingly, some studies report known group differences between patients with persistent neck pain and healthy controls for TPDT where others have not (Harvie et al., 2018; Elsig et al., 2014). And lastly, it is possible that patients with chronic neck pain may not have impaired localisation or orientation accuracy using vibrotactile stimuli. Although both the iTAD and TPDT aim to measure the same construct, they most likely measure different aspects of tactile acuity, given the distinct difference in the nature of the stimulus (light touch vs vibrations) as well as the task. However, impairments in localisation and orientation type tasks have previously been demonstrated in chronic pain using light touch (Harvie et al., 2018; Maihofner et al., 2006; Wand et al., 2013b; Zamorano et al., 2015).

One limitation of the iTAD may be the use of vibration as a stimulus, given its transmission through tissue. However, inverse square law dictates that the intensity and amplitude of the vibration decreases as it moves away from the source, such that the vibration will be the strongest under the area of the node. Additionally, absorption causes further attenuation of the vibration as it moves through the tissue. Accordingly, previous studies have reported the possibility of accurate vibration localisation with even smaller inter node distances (van Erp, 2005; de Jesus Oliveira et al., 2016; Johannesson et al., 2017; Hoffmann et al., 2018).

Another limitation for the construct validity study is that we did not perform neurological examination. Although the selection criteria aimed to exclude patients with neurological disorders, loss of sensory function (a known cause for reduced tactile acuity) cannot be ruled out. Additionally, since a loss of sensory function has also been demonstrated in patients with chronic pain without neuropathic involvement (Voerman et al., 2000; Puta et al., 2013), sensory tests may have been informative of the underlying mechanisms of the difference in tactile acuity. This is especially interesting, since the relationship between vibration detection and localisation may not be straightforward (Cholewiak and Collins, 2003; Harris et al., 2004).

In conclusion, the iTAD prototype shows promise in testing tactile acuity, especially using the overall score. However, further fine-tuning is needed before the iTAD can be introduced in clinic.

Ethical approval

Studies were approved by the Ethics Committee of Griffith University (Reference #2016/168).

Fig. 3. Mean and 95% confidence intervals of the mean for raw data of accuracy scores for both healthy individuals and patients with persistent neck pain. Scores presented for the total sample ($n = 60$), men only ($n = 28$) and women only ($n = 32$). * indicates a significant difference ($p < 0.05$).

Source of funding

Daniel S. Harvie is supported by an Early Career Research Fellowship from the National Health and Medical Research Council of Australia (Grand ID APP1142929). M. Sterling received a Fellowship from the National Health and Medical Research Council of Australia. In the last 5 years, G. Lorimer Moseley has received support from: Pfizer Australia, Seqirus, Kaiser Permanente, Workers' Compensation Boards in Australia, Europe and North America, AIAAustralasia, the International Olympic Committee, Port Adelaide Football Club and Arsenal Football Club. Professional and scientific bodies have reimbursed him for travel costs related to presentation of research on pain at scientific conferences/symposia. He has received speaker fees for lectures on pain and rehabilitation.

Declaration of competing interest

Authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.msksp.2020.102259>.

References

- Bartlett, J.W., Frost, C., 2008. Reliability, repeatability and reproducibility: analysis of measurement errors in continuous variables. *Ultrasound Obstet. Gynecol.* 31, 466–475.
- Catley, M.J., Tabor, A., Wand, B.M., Moseley, G.L., 2013. Assessing tactile acuity in rheumatology and musculoskeletal medicine—how reliable are two-point discrimination tests at the neck, hand, back and foot? *Rheumatology* 52, 1454–1461.
- Catley, M.J., O'Connell, N.E., Berryman, C., Ayhan, F.F., Moseley, G.L., 2014. Is tactile acuity altered in people with chronic pain? a systematic review and meta-analysis. *J. Pain* 15, 985–1000.
- Cholewiak, R.W., Collins, A.A., 2003. Vibrotactile localization on the arm: effects of place, space, and age. *Percept. Psychophys.* 65, 1058–1077.
- Craig, J.C., Johnson, K.O., 2000. The two-point threshold: not a measure of tactile spatial resolution. *Curr. Dir. Psychol. Sci.* 9, 29–32.
- de Jesus Oliveira, Nedel, L., Maciel, A., Brayda, L., 2016. Spatial discrimination of vibrotactile stimuli around the head. In: 2016 IEEE Haptics Symposium (HAPTICS), pp. 1–6.
- de Vet, H.C., Terwee, C.B., Knol, D.L., Bouter, L.M., 2006. When to use agreement versus reliability measures. *J. Clin. Epidemiol.* 59, 1033–1039.
- Di Pietro, F., McAuley, J.H., Parkitny, L., et al., 2013. Primary somatosensory cortex function in complex regional pain syndrome: a systematic review and meta-analysis. *J. Pain* 14, 1001–1018.
- Elsig, S., Luomajoki, H., Sattelmayer, M., Taeymans, J., Tal-Akabi, A., Hilfiker, R., 2014. Sensorimotor tests, such as movement control and laterality judgment accuracy, in persons with recurrent neck pain and controls. A case-control study. *Man. Ther.* 19, 555–561.
- Flor, H., Denke, C., Schaefer, M., Grusser, S., 2001. Effect of sensory discrimination training on cortical reorganization and phantom limb pain. *Lancet* 357, 1763–1764.
- Giavarina, D., 2015. Understanding bland altman analysis. *Biochem. Med.* 25, 141–151.
- Harris, J.A., Thein, T., Clifford, C.W., 2004. Dissociating detection from localization of tactile stimuli. *J. Neurosci.* 24, 3683–3693.
- Harvie, D.S., Kelly, J., Buckman, H., et al., 2017. Tactile acuity testing at the neck: a comparison of methods. *Musculoskeletal Science and Practice* 32, 23–30.
- Harvie, D.S., Edmond-Hank, G., Smith, A.D., 2018. Tactile acuity is reduced in people with chronic neck pain. *Musculoskeletal Sci Pract* 33, 61–66.
- Henry, D.E., Chiodo, A.E., Yang, W., 2011. Central nervous system reorganization in a variety of chronic pain states: a review. *PM&R.* 3, 1116–1125.
- Hoffmann, R., Valgeirsdottir, V.V., Johannesson, O.I., Unnthorsson, R., Kristjansson, A., 2018. Measuring relative vibrotactile spatial acuity: effects of tactor type, anchor points and tactile anisotropy. *Exp. Brain Res.* 236, 3405–3416.
- Hopkins, W.G., 2000. Measures of reliability in sports medicine and science. *Sports Med.* 30, 1–15.
- Johannesson, O.I., Hoffmann, R., Valgeirsdottir, V.V., Unnthorsson, R., Moldoveanu, A., Kristjansson, A., 2017. Relative vibrotactile spatial acuity of the torso. *Exp. Brain Res.* 235, 3505–3515.
- Kimberlin, C.L., Winterstein, A.G., 2008. Validity and reliability of measurement instruments used in research. *Am. J. Health Syst. Pharm.* 65, 2276–2284.
- Koo, T.K., Li, M.Y., 2016. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine* 15, 155–163.
- Kuroki, S., Watanabe, J., Nishida, S., 2017. Integration of vibrotactile frequency information beyond the mechanoreceptor channel and somatotopy. *Sci. Rep.* 7, 2758.
- Luedtke, K., Adamczyk, W., 2017. Tactile acuity in the neck: calling for more basic science research. *Musculoskeletal Sci Pract* 32, 127–128.
- Luedtke, K., Adamczyk, W., Mehrtens, K., et al., 2018. Upper cervical two-point discrimination thresholds in migraine patients and headache-free controls. *J. Headache Pain* 19, 47.
- Maihofner, C., Neundorfer, B., Birklein, F., Handwerker, H.O., 2006. Mislocalization of tactile stimulation in patients with complex regional pain syndrome. *J. Neurol.* 253, 772–779.
- Makin, T.R., Filippini, N., Duff, E.P., Henderson Slater, D., Tracey, I., Johansen-Berg, H., 2015. Network-level reorganisation of functional connectivity following arm amputation. *Neuroimage* 114, 217–225.
- Mancini, F., Wang, A.P., Schira, M.M., et al., 2019. Fine-grained mapping of cortical somatotopies in chronic complex regional pain syndrome. *J. Neurosci.* 39, 9185–9196.
- McGraw, K.O., Wong, S.P., 1996. Forming inferences about some intraclass correlation coefficients. *Psychol. Methods* 1, 30–46.
- Miller, G.A., Chapman, J.P., 2001. Misunderstanding analysis of covariance. *J. Abnorm. Psychol.* 110, 40–48.
- Mokkink, L.B., Terwee, C.B., Patrick, D.L., et al., 2010. The COSMIN study reached international consensus on taxonomy, terminology, and definitions of measurement properties for health-related patient-reported outcomes. *J. Clin. Epidemiol.* 63, 737–745.
- Moseley, G.L., Zalucki, N.M., Wiech, K., 2008. Tactile discrimination, but not tactile stimulation alone, reduces chronic limb pain. *Pain* 137, 600–608.
- Pearce, N., 2016. Analysis of matched case-control studies. *BMJ* 352, i969.
- Pinna, G.D., Maestri, R., Torunski, A., et al., 2007. Heart rate variability measures: a fresh look at reliability. *Clin. Sci. (Lond.)* 113, 131–140.
- Pleger, B., Dinse, H.R., Ragert, P., Schwenkreis, P., Malin, J.P., Tegenthoff, M., 2001. Shifts in cortical representations predict human discrimination improvement. *Proc. Natl. Acad. Sci. U. S. A.* 98, 12255–12260.
- Pleger, B., Tegenthoff, M., Ragert, P., et al., 2005. Sensorimotor retuning [corrected] in complex regional pain syndrome parallels pain reduction. *Ann. Neurol.* 57, 425–429.
- Pleger, B., Ragert, P., Schwenkreis, P., et al., 2006. Patterns of cortical reorganization parallel impaired tactile discrimination and pain intensity in complex regional pain syndrome. *Neuroimage* 32, 503–510.
- Portney, L.G., Watkins, M.P., 2009. Foundations of Clinical Research: Applications to Practice, 892. Pearson/Prentice Hall Upper, Saddle River, NJ.
- Putz, C., Schulz, B., Schoeler, S., et al., 2013. Somatosensory abnormalities for painful and innocuous stimuli at the back and at a site distinct from the region of pain in chronic back pain patients. *PLoS One* 8, e58885.
- Ribeiro, M.J., Paiva, J.S., Castelo-Branco, M., 2016. Spontaneous fluctuations in sensory processing predict within-subject reaction time variability. *Front. Hum. Neurosci.* 10, 200.
- Saville, C.W.N., Pawling, R., Trullinger, M., Daley, D., Intriligator, J., Klein, C., 2011. On the stability of instability: optimising the reliability of intra-subject variability of reaction times. *Pers. Individ. Differ.* 51, 148–153.
- Taber, K.S., 2018. The use of cronbach's alpha when developing and reporting research instruments in science education. *Res. Sci. Educ.* 48, 1273–1296.
- van Erp, 2005. Vibrotactile spatial acuity on the torso: effects of location and timing parameters. In: First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems World Haptics Conference, pp. 80–85.
- Voerman, V.F., van Egmond, J., Crul, B.J., 2000. Elevated detection thresholds for mechanical stimuli in chronic pain patients: support for a central mechanism. *Arch. Phys. Med. Rehabil.* 81, 430–435.
- Wand, B.M., Abbaszadeh, S., Smith, A.J., Catley, M.J., Moseley, G.L., 2013a. Acupuncture applied as a sensory discrimination training tool decreases movement-related pain in patients with chronic low back pain more than acupuncture alone: a randomised cross-over experiment. *Br. J. Sports Med.* 47, 1085–1089.
- Wand, B.M., Keeves, J., Bourgoin, C., et al., 2013b. Mislocalization of sensory information in people with chronic low back pain: a preliminary investigation. *Clin. J. Pain* 29, 737–743.
- Weir, J.P., 2005. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J. Strength Condit Res.* 19, 231–240.
- Zamorano, A.M., Riquelme, I., Kleber, B., Altenmüller, E., Hatem, S.M., Montoya, P., 2015. Pain sensitivity and tactile spatial acuity are altered in healthy musicians as in chronic pain patients. *Front. Hum. Neurosci.* 8, 1016.