Research Report

Tension of the Ulnar, Median, and Radial Nerves During Ulnar Nerve Neurodynamic Testing: Observational Cadaveric Study

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Abstract

Background. The ulnar nerve neurodynamic test (ULNT3) uses upper limb positioning to investigate symptoms arising from the ulnar nerve. It is proposed to selectively increase tension of the nerve, however this is not well established.

Objective. To determine the upper limb position that results in: (1) the greatest tension of the ulnar nerve and (2) the greatest difference in tension between the ulnar nerve and the other two major nerves of the upper limb: median and radial.

Design. Observational cadaver study.

Methods. Tension (Newtons) of the ulnar, median and radial nerves was measured simultaneously using three buckle force transducers during five upper limb positions in 10 embalmed human cadavers (n=20 limbs). Repeated measures analysis of variance (ANOVA) with Bonferroni post-hoc tests determined differences in tension between nerves and between limb positions.

Results. The addition of shoulder horizontal abduction (H.Abd; 12.62N; 95% CI 10.76, 14.47) and combined shoulder abduction and internal rotation (H.Abd+IR; 11.86N; 9.96, 13.77) to ULNT3 (scapular depression, shoulder abduction and internal rotation, elbow flexion, forearm pronation, wrist and finger extension) produced significantly greater ulnar nerve tension compared to ULNT3 alone (8.71N; 7.25, 10.17; \( P \leq 0.01 \)).

ULNT3+H.Abd demonstrated the greatest difference in tension between nerves (mean difference between ulnar and median 11.87N; 95% CI 9.80, 13.92; between ulnar and radial 8.47N; 6.41, 10.53, \( P < .01 \)).
Limitations. These results pertain only to the biomechanical plausibility of ulnar nerve neurodynamic and do not account for other factors that may effect the clinical application of this test.

Conclusion. ULNT3+H.Abd is a biomechanically plausible test for detecting peripheral neuropathic pain related to the ulnar nerve. In situations, where the shoulder complex will not tolerate the combination of shoulder external rotation in abduction performing ULNT with internal rotation instead of external rotation, is a biomechanically plausible alternative.
Introduction

The ulnar, median and radial nerve upper limb neurodynamic tests (ULNTs) are designed to assess the interplay between mechanics and physiology of the three major nerves of the arm.\(^1\) The ulnar nerve bias ULNT (ULNT3) is purported to examine the ulnar nerve to determine its contribution to neuropathic symptoms of the upper limb or neck.\(^2,3\) The validity of ULNT3 is based on its ability to selectively increase tension of the ulnar nerve, without increasing tension of adjacent tissue \(^2,4,5\). It is generally accepted that this mechanical provocation is responsible for reproduction of the patient’s symptoms.\(^6,7\) However, there is evidence from one previous human cadaveric study that ULNT3 may not selectively increase tension of the ulnar nerve.\(^8\)

Of clinical importance, neurodynamics is complex and involves consideration of both central and homeostatic mechanisms.\(^10\) Therefore the outcome of a ULNT is not solely due to the development of tension within the nervous system. It fact, it may be altered by nerve excursion\(^33,34\) and compression,\(^35\) physiological events,\(^6,36,37\) psychosocial factors\(^38,39\) or whether a patient’s symptoms are centrally or peripherally mediated.\(^10,40\) However, an understanding of the development of tensile force in the nervous system in response to upper limb movement remains important as it provides a foundation for the plausibility of an ULNT to detect peripheral neuropathic pain.

The movements that comprise ULNT3 are based on the anatomical course of the ulnar nerve with respect to the joint axes of the upper limb.\(^2,9\) Originally these movements included: scapular depression, shoulder abduction and external rotation, elbow flexion, forearm supination and wrist and finger extension.\(^3\) However, a
modification to ULNT3 was later proposed, suggesting that forearm pronation replace supination. This occurred as it was observed that forearm pronation increases the distance between the medial epicondyle of the humerus and the pisiform, theoretically increasing tension of the ulnar nerve. Despite this anatomical hypothesis, there were no identified studies comparing tension of the ulnar nerve between these two variations of ULNT3. Therefore it remains unclear as to whether forearm pronation or supination should be included as a component of the test.

The ability of ULNT3 to selectively increase tension of the ulnar nerve is currently unclear. One previous human cadaveric study measured tension of the ulnar, median and radial nerves simultaneously in the axilla and found that ULNT3 with forearm supination failed to increase tension of the ulnar nerve significantly more than the median or radial nerves. Therefore, ULNT3 may not effectively differentiate between neuropathic symptoms arising from the three major nerves of the arm. Supporting this, previous human cadaveric studies have shown that shoulder external rotation, a standard component of ULNT3, does not increase tension of the cords of the brachial plexus or peripheral nerves when measured in the axilla. Additionally, the application of shoulder external rotation in abduction has been shown to stress the non-neural structures of the anterior shoulder. This may affect the clinical utility of ULNT3 as patients with certain shoulder pathologies or those with pain that is highly irritable may not tolerate this position. Despite several studies investigating tension of the ulnar nerve during different upper limb positions, the most effective upper limb position for ULNT3 remains undefined.
The purpose of this study was to determine the upper limb position that results in:
(1) the greatest tension of the ulnar nerve and (2) the greatest difference in tension
between the ulnar nerve and the other two major nerves of the upper limb: median and
radial. This position will constitute a biomechanically plausible upper limb
neurodynamic test for the ulnar nerve based on the development of tensile force within
the nervous system. As such it may contribute to more accurate clinical interpretation of
symptom reproduction during testing. This may improve the clinical detection of
neuropathic pain related to the ulnar nerve.

Methods

Prior to the commencement of data collection, 10 cadaver specimens ethically
approved for anatomical dissection at the University of Newcastle and not used for the
collection of ulnar nerve tension data were examined to generate hypotheses about the
upper limb positions most likely to induce the greatest tension of the ulnar nerve. This
was necessary as measuring tension in all of the possible upper limb positions was not
feasible (i.e., all possible combinations of movements at the neck, shoulder, elbow, wrist
and fingers). These anatomical observations revealed that the distance between the
medial humeral epicondyle and the bifurcation of the medial cord of the brachial plexus
was greater with shoulder internal rotation compared to external rotation in 90° shoulder
abduction, suggesting the ulnar nerve would have to traverse further during internal
rotation, theoretically increasing its tension. It was also observed that with the shoulder
in the position for ULNT3 (110° abduction and 90° external rotation), the ulnar nerve
runs anterior to the glenohumeral joint axis. It was therefore hypothesised that the addition of shoulder horizontal abduction (defined as movement of the humerus posteriorly in the transverse plane with the shoulder abducted to approximately 90°) to ULNT3 would also increase tension of the ulnar nerve. From these observations, the upper limb positions to be tested were determined. The five test positions included: (1) ULNT3 (scapula depression, shoulder abduction and external rotation, elbow flexion, forearm pronation, wrist and finger extension), (2) ULNT3 with shoulder internal instead of external rotation (ULNT3+IR), (3) ULNT3 with forearm supination instead of pronation (ULNT3+Sup), (4) ULNT3 with the addition of shoulder horizontal abduction (ULNT3+H.Abd, Figure 1, a and b) and (5) ULNT3 with shoulder internal instead of external rotation and with the addition of horizontal abduction (ULNT3 + IR + H.Abd, Figure 1, c and d) (Table 1).

Data were collected from 10 whole body human cadavers (mean age at time of death: 81 years, range 65-94). All test procedures were applied to both upper limbs (n=20 limbs). The cadavers were embalmed less than 48 hours after death with Arterial Anatomical NF embalming fluid (Genelyn Pty Ltd, Marden, S.A., Australia). Kleinrensink et al. 22 demonstrated a strong positive correlation in tensile force data between embalmed and unembalmed specimens, suggesting the use of embalmed specimens would provide acceptable data for comparing tensile force in the upper limb nerves.

Cadavers that had been donated to the University of Newcastle Body Donor Program were considered for entry into the study (in June 2011). Ethical approval for the
study was obtained from The University of Newcastle Human Research Ethics Committee. Cadavers were excluded from the study if they were found to have evidence of communicable disease, shoulder pathology, or if they failed to meet the following range of motion criteria required for testing using usual clinical methods: shoulder abduction > 100°, shoulder external rotation > 60°, shoulder internal rotation > 60°, elbow flexion > 140° and wrist extension > 30°. Out of 15 cadavers examined, five were excluded due to inadequate joint ROM.

2.1 Sample Size and Dissection

A sample size of 10 cadavers was used in this study, which equates to 20 upper limbs. Anatomical studies published in the literature typically have sample sizes similar to this study.8,16 The ulnar, median and radial nerves were exposed in the axilla of both upper limbs through removal of the skin and subcutaneous tissue in a 10cm x 5cm window overlying the nerves. To preserve the relationship between the nerves and surrounding tissue, care was taken to remove as minimal tissue as possible and still allow attachment of the three buckle force transducers.

2.2. Instruments

The present study defined tension as the longitudinal force applied to a nerve in response to movement of the upper limb.3 Tension of the ulnar, median and radial nerves was measured in Newtons using buckle force transducers. Similar transducers have been
tested and found to be highly reliable and consistent using non-biological tissues,\textsuperscript{24} and human peripheral nerve tissue.\textsuperscript{8, 22}

To allow for reliable comparison between the nerves during positioning, a buckle force transducer was attached to each of the radial, ulnar and median nerves at two, five and eight centimeters distal to the inferior border of the latissimus dorsi tendon, respectively (Figure 2). Changes in alignment of nerve tissue in the buckle have been shown to affect the amplitude of tension.\textsuperscript{24} Therefore, the position of the three buckles was visually inspected before the commencement of each test procedure to ensure the bridges were fixed perpendicularly to each nerve.

The design of the buckle force transducer used in this study is shown in Figure 3. A rectangular frame lies over a nerve, with a bridge that is passed beneath the nerve and on top of the frame. As longitudinal force is applied to the nerve, it straightens, causing the bridge to exert a force on the frame. This force is detected by a force transducer (Applied Measurement, Eastwood, NSW, Australia), which is attached to the longer side of the frame. The force transducer forms one limb of a Wheatstone bridge circuit such that changes in tensile force are represented as voltage. Voltage from the strain gauge was displayed continuously Labview Version 10.0 (National Instruments, Australia). For each measure of tension in each limb position, data were collected for 5 seconds at 100 Hz, with the mean value of these 500 data points representing the nerve tension. This allowed comparison between the three nerves for each position. These data were converted to Newtons for analysis and presentation.
2.3. Test Procedure

Each cadaver was placed supine, in the anatomical position. The cadaver was then placed diagonally across the examination table so that the axis of the glenohumeral joint lay just off the table to facilitate scapular depression and shoulder horizontal abduction. Changes in the orientation of the cervical spine, thoracic spine, and the three non-test limbs have been shown to alter tension of the upper limb nerves. Therefore, to ensure reliable comparison between cadavers, these body segments were stabilised using sandbags and straps to the head, thorax and lower limbs.

A single trial consisted of measuring tension at the starting position, at five test positions (Table 1), then again on return to the starting position. One examiner (NT) performed three trials of each test position and an average value was calculated and used for analysis. A second examiner (JM) repeated the test procedure for ULNT3, ULNT3+H.Abd, and ULNT3 + H.Abd +IR to determine inter-rater reliability of tension measurement for these positions. The examiner conducting the test procedure was blinded to the tension data being recorded.

For each upper limb test position, the amount of shoulder abduction and elbow flexion were standardised using conventional goniometry, which has been shown to be reliable when measured by a single assessor. All other joints were moved to the maximum available range of motion, as these movements could not be reliably measured during the test procedure.
To ensure reliable comparison between trials a fixed protocol for the sequencing of each position was adopted (Table 1). The sequence of the five positions was not randomised between trials to allow detection of potential hysteresis across each limb. When the end point of a particular position was achieved five seconds of continuous tension data for each nerve was recorded and averaged. The force transducer was zeroed at the start of the sequence but was not zeroed between each test position. This allowed for comparison of tension between the initial starting (resting) position and the final resting position for the entire sequence, to determine the degree of hysteresis, if any, in each nerve.

2.4. Data Analysis

2.4.1 Reliability

Reliability of positioning the upper limb was calculated using intraclass correlation coefficients (ICC) using two-way mixed effects models for absolute agreement. Incorporating data from the three nerves, intra-rater reliability was calculated using the three trials performed by the first examiner for each position. Inter-rater reliability was calculated using the mean of the three trials between the first and second examiners for ULNT3, ULNT3+H.Abd, and ULNT3 + H.Abd +IR. The standard error of measurement (SEM) was calculated using the formula SD × √1-r, where SD is the standard deviation of all values of the compared trials (3 trials for intra-rater, and 2
trials for inter-rater comparisons) and r is the ICC value. The smallest detectable
difference at a 95% confidence level (SDD(95)) was calculated using the formula

$$1.96 \times \sqrt{n} \times SEM,$$

where n is the number of compared trials (3 for intra-rater and 2 for
inter-rater analyses).

2.4.2 Hysteresis

Paired sample t-tests were used to compare nerve tension for each nerve between
the initial starting (resting) position at the start of all trials and the final resting position at
the end of the all trials performed by examiner one. This determined the possible effect
of hysteresis on each of the three nerves.

2.4.3 The effect of limb position on tension

The effect of limb position on tension was calculated using the mean of three
trips performed by the first examiner for each position. Data were checked for normality
prior to analyses. Descriptive statistics were used to calculate average tension for the
radial, median and ulnar nerves for each of the five test positions. A repeated measures
analysis of variance (ANOVA) was used to determine the effects of limb position and
nerve on the measured tension. A significant position x nerve interaction indicated a
significant effect of position and nerve on tension. Bonferroni post-hoc tests determined
if tension of the ulnar nerve was significantly different between limb positions. Further
comparisons using Bonferroni post-hoc tests determined whether there was a difference in tension between the three upper limb nerves for each limb position.

Results

3.1. Reliability

Intra and inter-rater reliability was excellent for all positions calculated (Table 2). Excellence was defined as ICC > 0.75.\textsuperscript{27} The SEM values across all tested limb positions were \( \leq 1.41 \) N, and the SDD(95) \( \leq 4.78 \) N (Table 2).

3.2. Hysteresis

There were no significant differences in mean resting tension observed between the initial starting (resting) position and the final resting positions for each of the three nerves. For the ulnar nerve, the mean starting tension measured over 10 seconds of continuous recording at 100 Hz was -0.21N (SD 0.48) and the mean ending tension was 0.02N (SD 0.60, p-value for the difference = .12), for the median nerve 0.02N (SD 0.53) and -0.22N (SD 0.57, p=.16), and for the radial nerve -0.11N (SD 0.58) and 0.01N (SD 0.94, p = .62). These very similar values for tension at the beginning and end of the sequence of limb positioning trials indicate that hysteresis did not occur.
3.3. The greatest ulnar nerve tension

Descriptive data are displayed in Table 3 for the three nerves in each of the five test positions. The ULNT3+H.Abd and ULNT3+H.Abd+IR positions produced significantly greater tension of the ulnar nerve compared to the ULNT3 \( (P \leq 0.01, \text{ Table 3}) \). The largest mean tension of the ulnar nerve occurred in the ULNT3+H.Abd position. ULNT3+Sup produced the least amount of tension of the ulnar nerve, significantly less tension than in the ULNT3 position \( (P < 0.01, \text{ Table 3}) \).

3.4. The greatest difference in tension between the ulnar, median and radial nerves

All positions resulted in significantly greater tension of the ulnar nerve compared to the median and radial nerves \( (P < 0.01, \text{ Table 3}) \). The ULNT3+H.Abd position showed the greatest difference in tension between ulnar and median (mean tension difference 11.87N; 95% CI 9.80, 13.92, \( P < 0.01 \)) and ulnar and radial (8.47N; 6.41, 10.53, \( P < 0.01 \)) nerves (Table 3). ULNT3+Sup resulted in the lowest mean difference between ulnar and median (5.25N; 95% CI 3.73, 6.77 \( P < 0.01 \)) and ulnar and radial (3.10N; 1.58, 4.61, \( P < 0.01 \)) nerves.

Discussion
The currently accepted ULNT3 with the addition of shoulder horizontal abduction (ULNT+H.Abd) and this position with the substitution of shoulder internal rotation for external rotation (ULNT3+H.Abd+IR) result in the greatest tension of the ulnar nerve and the greatest difference in tension between the ulnar nerve and the other two major nerves of the upper limb: median and radial. These positions constitute biomechanically plausible upper limb neurodynamic tests for the ulnar nerve based on the development of tensile force within the nervous system. Their application clinically may contribute to more accurate interpretation of symptom reproduction during testing, which may improve the clinical detection of neuropathic pain related to the ulnar nerve.

4.1. The greatest ulnar nerve tension

The position generating the greatest tension of the ulnar nerve was determined by measuring the magnitude of tension of the ulnar nerve when it was placed in various upper limb positions. The ULNT3+H.Abd position (Figure 1, a and b) generated the largest mean tension of the ulnar nerve. This was significantly higher than that produced in any other of the tested positions. In fact, ULNT3+H.Abd produced 45% more tension of the ulnar nerve compared to ULNT3 alone. In terms of tensile force, this upper limb position may be the most likely to detect neuropathic pain arising from the ulnar nerve and the position least likely to produce a false negative test. However, in the clinical context placing the shoulder towards end range abduction and external rotation may not be tolerated by some patients due to the stress that this position places on non-neural
In such instances the ULNT3+H.Abd+IR position (Figure 1, c and d) may be a more suitable test as it utilises shoulder internal rotation rather than external, potentially decreasing stress on the anterior shoulder while also producing significantly greater tension of the ulnar nerve compared to ULNT3 alone. Similarly, patients with shoulder pain arising from causes such as subacromial impingement syndrome may not tolerate end range horizontal abduction and internal rotation. Therefore, the use of either ULNT3 variation should be balanced against the potential sensitivity of local non-neural shoulder structures.

4.2. The greatest difference in tension between the ulnar, median and radial nerves

The position that generated the greatest difference in tension between the three nerves of the upper limb was determined by comparing the tension between the ulnar, median and radial nerves for each tested upper limb position. That is, the greater the difference in tension between the ulnar nerve and the other two nerves (median and radial), the greater the capacity of that limb position for detecting ulnar nerve tension without inducing tension in the other upper limb nerves. Though in all test positions there were statistical differences in tension between the three upper limb nerves, the ULNT3+H.Abd position produced the greatest difference in tension between the ulnar nerve and the other two nerves. In terms of tensile force, this upper limb position may be the most likely to differentiate neuropathic pain arising from the three major nerves of the arm and the position least likely to produce a false positive test. However, patients
with pre-existing shoulder pathology or highly irritable symptoms may not tolerate the addition of horizontal abduction to an abducted and externally rotated shoulder.\textsuperscript{2,15,28} In such patients, the ULNT3+H.Abd+IR position may be used as an alternative to ULNT3+H.Abd, as it also displayed comparatively large differences between the three upper limb nerves.

4.3 The inclusion of forearm pronation

The currently accepted ULNT3 includes forearm pronation rather than supination, as anatomical observations suggest that the ulnar nerve would have to traverse further during pronation, theoretically increasing its tension\textsuperscript{10}. However, there were no identified studies comparing tension of the nerve in these two variations of ULNT3. The present study revealed that ULNT3 generated significantly greater tension of the ulnar nerve compared to ULNT3+Sup. Similarly, Wright et al., 2001 when measuring strain at the elbow and wrist in five fresh frozen transthoracic specimens found that a composite position: 110 degrees shoulder abduction, elbow flexion, forearm pronation, radial deviation, wrist and finger extension produced the greatest strain of the ulnar nerve at the elbow and wrist. This lends support to the inclusion of pronation rather than supination as a component of an ulnar nerve bias ULNT. However, Wright et al., 2001 did not compare this position to one including supination.

The present study also revealed that both ULNT3 and ULNT3+Sup created a statistically significant difference in tension between all three major nerves of the upper
limb. This contrasts the findings of Kleinrensink et al. who demonstrated that ULNT3+Sup failed to significantly increase tension of the ulnar nerve relative to the other two major nerves of the upper limb. The disparity between these findings may be due to the amount of tissue removed in each study, as it has been shown that the tissue surrounding a nerve affects tension development. Alternatively, it may be due to the discrepancy in elbow flexion range, i.e., 140° in the present study compared to 120° in Kleinrensink et al., as elbow flexion causes the greatest tension of the ulnar nerve. Although the current study demonstrated ULNT3+Sup resulted in significantly greater tension of the ulnar nerve compared to the median and radial nerves, this position produced the lowest mean difference in tension between all three nerves. Therefore, the findings of the present study suggest the use of forearm pronation is preferred over supination for increasing tension in the ulnar nerve. This supports the inclusion of pronation as a component of the currently used ULNT3.

4.5. Clinical implications

The ability of an ULNT to selectively increase tension of its intended nerve provides a foundation for its plausibility to detect peripheral neuropathic pain. An ULNT should be able to reproduce a patient’s symptoms in the sensory distribution of its intended nerve. In addition, the use of a structural differentiation maneuverer should change these symptoms. This is the process used clinically to confirm the presence of neuropathic pain arising from a peripheral nerve. It has been demonstrated that the
median nerve bias ULNT is biomechanically plausible\textsuperscript{8} and that the use of this test clinically reproduces sensory responses in asymptomatic subjects in the distribution of the median nerve.\textsuperscript{2,31} The present study suggests that the current clinical test ULNT3 with forearm pronation is biomechanically plausible based on development of tension in the upper limb nerves, and its use clinically has been shown to reproduce symptoms in the distribution of the ulnar nerve.\textsuperscript{10,32,39} However, Martinez et al.\textsuperscript{40} demonstrated that the application of ULNT3 in asymptomatic individuals produced sensory responses in 21 different areas of the upper limb, neck and face. While sensory responses occurred predominantly in the medial forearm (the distribution of the ulnar nerve), they were also reported in similar frequency in the lateral forearm and hand (the distribution of the radial and median nerves). In addition, the present study demonstrated ULNT3+H.Abd and ULNT3+H.Abd+IR (Figure 1) resulted in greater tension of the ulnar nerve and a greater difference in tension between the three major nerves of the arm. Therefore these positions may be more likely to elicit symptoms in the distribution of the ulnar nerve, without evoking symptoms from the median or radial nerves. Importantly, this may enhance the ability of the clinician to accurately detect neuropathic pain related to the ulnar nerve.

4.6. Limitations

Tension of adjacent non-neural tissue, for example the subclavian artery, has also been documented in cadaveric studies during upper limb neurodynamic tests.\textsuperscript{41-43} Therefore, as the current study did not measure tension of non-neural tissue, conclusions
regarding the biomechanical plausibility of ulnar nerve neurodynamic testing are only related to comparisons made between the three nerves. However, due to the unique course of the ulnar nerve in the upper limb, it is unlikely that the combination of movements that comprise an ulnar nerve neurodynamic test will result in greater tension of non-neural tissue compared to the ulnar nerve, as the majority of this tissue is either mono or bi-articular.

4.7. Future Research

Clinical evaluation is needed to verify the utility of ULNT3+H.Abd and ULNT3+H.Abd+IR in light of the multiple variables that may impact the clinical interpretation of a neurodynamic test. Normative data for joint range of motion and symptom response to the proposed positions needs to be established in asymptomatic patients. Furthermore, the ability of this test to detect ulnar nerve pathology in symptomatic patients should be compared to alternate diagnostic methods to determine the clinical utility of these test positions.

Conclusion

The authors propose a biomechanically plausible test to detect neuropathic pain related to the ulnar nerve. The test consists of the currently described ULNT3 (scapular depression, shoulder abduction and internal rotation, elbow flexion, forearm pronation, wrist and
finger extension) with the addition of horizontal abduction. In clinical situations where the non-neural tissues of the anterior shoulder complex will not tolerate the combination of abduction, external rotation, and horizontal abduction, performing ULNT3 with internal rotation instead of external rotation may be a biomechanically plausible alternative for detecting peripheral neuropathic pain related to the ulnar nerve. However, as multiple variables may affect the clinical interpretation of these tests further investigation is required to determine whether these results translate to clinical practice.
Acknowledgements

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References


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Table 1. The five upper limb positions used to compare tension in the nerves of the upper limb.

<table>
<thead>
<tr>
<th>Position</th>
<th>Scapular</th>
<th>Shoulder</th>
<th>Elbow</th>
<th>Forearm</th>
<th>Wrist</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULNT3\textsuperscript{a}</td>
<td>Depression</td>
<td>110° Abduction, 140° Flexion Pronation Extension</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULNT3+IR\textsuperscript{b}</td>
<td>Depression</td>
<td>\textbf{80° Abduction}, 140° Flexion Pronation Extension</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULNT3+Sup\textsuperscript{c}</td>
<td>Depression</td>
<td>110° Abduction, 140° Flexion Supination Extension</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULNT3+H.Abd\textsuperscript{d}</td>
<td>Depression</td>
<td>110° Abduction, 140° Flexion Pronation Extension</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULNT3+H.Abd+IR\textsuperscript{e}</td>
<td>Depression</td>
<td>\textbf{80° Abduction}, 140° Flexion Pronation Extension</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{a}Upper limb neurodynamic test 3 (ULNT3) as described by Butler (2000) (scapula depression, abduction, ER, elbow flexion, pronation, wrist and finger extension)
\textsuperscript{b}ULNT3 with internal rotation (IR)
\textsuperscript{c}ULNT3 with forearm supination (Sup)
\textsuperscript{d}ULNT3 with horizontal abduction (H.Abd)
\textsuperscript{e}ULNT3 with horizontal abduction and internal rotation (+IR +H.Abd)
* Movements in \textbf{bold font} have been added to the end position of ULNT3
Table 2. Intra- and inter-rater reliability, standard error of measurement (SEM) and smallest detectable difference at a 95% confidence interval of tension measurements for the five neurodynamic test positions for the ulnar nerve.

<table>
<thead>
<tr>
<th>Position</th>
<th>ICC</th>
<th>95% CI</th>
<th>SEM</th>
<th>SDD(95)</th>
<th>ICC</th>
<th>95% CI</th>
<th>SEM</th>
<th>SDD(95)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULNT3\textsuperscript{a}</td>
<td>0.92</td>
<td>0.88-0.95</td>
<td>1.20</td>
<td>4.07</td>
<td>0.90</td>
<td>0.83-0.94</td>
<td>1.20</td>
<td>3.34</td>
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<tr>
<td>ULNT3+IR\textsuperscript{b}</td>
<td>0.95</td>
<td>0.92-0.97</td>
<td>1.04</td>
<td>3.54</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULNT3+Sup\textsuperscript{c}</td>
<td>0.91</td>
<td>0.86-0.94</td>
<td>0.89</td>
<td>3.03</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ULNT3+H.Abd\textsuperscript{d}</td>
<td>0.94</td>
<td>0.91-0.96</td>
<td>1.41</td>
<td>4.78</td>
<td>0.96</td>
<td>0.93-0.97</td>
<td>1.09</td>
<td>3.03</td>
</tr>
<tr>
<td>ULNT3+H.Abd+IR\textsuperscript{e}</td>
<td>0.95</td>
<td>0.93-0.97</td>
<td>1.21</td>
<td>4.09</td>
<td>0.92</td>
<td>0.87-0.95</td>
<td>1.21</td>
<td>4.17</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Upper limb neurodynamic test 3 (ULNT3) as described by Butler (2000) (scapula depression, abduction, ER, elbow flexion, pronation, wrist and finger extension)

\textsuperscript{b}ULNT3 with internal rotation (IR)

\textsuperscript{c}ULNT3 with forearm supination (Sup)

\textsuperscript{d}ULNT3 with horizontal abduction (H.Abd)

\textsuperscript{e}ULNT3 with horizontal abduction and internal rotation (+IR +H.Abd)

* The second examiner did not record data for +IR and +SUP
Table 3. Mean, SD (95% CI) tension (N) of the Ulnar (U), Median (M) and Radial (R) nerves and mean differences in tension between the nerves for each of the five test positions.

<table>
<thead>
<tr>
<th>Position</th>
<th>Ulnar nerve</th>
<th>Median nerve</th>
<th>Radial nerve</th>
<th>U-M</th>
<th>U-R</th>
<th>R-M</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULNT3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8.71, 3.12 (7.25, 10.17)</td>
<td>0.40, 1.01 (-0.07, 0.87)</td>
<td>3.48, 2.26 (2.42, 4.53)</td>
<td>8.31 (6.52, 10.11)**</td>
<td>5.24 (3.44, 7.03)**</td>
<td>3.08 (1.28, 4.87)**</td>
</tr>
<tr>
<td>ULNT3+IR&lt;sup&gt;b&lt;/sup&gt;</td>
<td>10.00, 3.54 (8.33, 11.65)</td>
<td>0.42, 0.78 (0.55, 0.78)</td>
<td>3.53, 1.57 (2.80, 4.26)</td>
<td>9.57 (7.80, 11.35)**</td>
<td>6.46 (4.68, 8.24)**</td>
<td>3.11 (1.34, 4.89)**</td>
</tr>
<tr>
<td>ULNT3+Sup&lt;sup&gt;c&lt;/sup&gt;</td>
<td>6.14, 2.42 (5.01, 7.27)*</td>
<td>0.89, 1.34 (0.26, 1.52)</td>
<td>3.04, 1.92 (2.15, 3.94)</td>
<td>5.25 (3.73, 6.77)**</td>
<td>3.10 (1.58, 4.61)**</td>
<td>2.15 (0.64, 3.67)**</td>
</tr>
<tr>
<td>ULNT3+H.Abd&lt;sup&gt;d&lt;/sup&gt;</td>
<td>12.62, 3.96 (10.76, 14.47)*</td>
<td>0.75, 0.90 (0.33, 1.17)</td>
<td>4.14, 2.10 (3.16, 5.13)</td>
<td>11.87 (9.80, 13.92)**</td>
<td>8.47 (6.41, 10.53)**</td>
<td>3.39 (1.33, 5.45)**</td>
</tr>
<tr>
<td>ULNT3+H.Abd+IR&lt;sup&gt;e&lt;/sup&gt;</td>
<td>11.86, 4.07 (9.96, 13.77)*</td>
<td>1.08, 0.93 (0.65, 1.52)</td>
<td>4.97, 2.87 (3.63, 6.31)</td>
<td>10.78 (8.50, 13.06)**</td>
<td>6.90 (4.62, 9.18)**</td>
<td>3.89 (1.61, 6.16)**</td>
</tr>
</tbody>
</table>

<sup>a</sup>Upper limb neurodynamic test 3 (ULNT3) as described by Butler (2000) (scapula depression, abduction, ER, elbow flexion, pronation, wrist and finger extension)
<sup>b</sup>ULNT3 with internal rotation (IR)
<sup>c</sup>ULNT3 with forearm supination (Sup)
<sup>d</sup>ULNT3 with horizontal abduction (H.Abd)
<sup>e</sup>ULNT3 with horizontal abduction and internal rotation (+IR +H.Abd)

*indicates significantly different mean tension ($P \leq 0.01$) in this position than ULNT3

**indicates significantly different tension ($P < 0.05$) between two nerves (e.g. U-M) for a given position (e.g. ULNT2b)
Figure 1. Anterior and lateral views of two variations of the current neurodynamic test for the ulnar nerve (ULNT3: scapula depression, shoulder abduction and external rotation, elbow flexion, pronation, wrist and finger extension). (a) and (b): the current test with addition of horizontal abduction (ULNT3+H.Abd); (c) and (d) the current test with the addition of horizontal abduction and internal rotation (ULNT3+H.Abd+IR). Arrows illustrate the direction of the additional horizontal abduction away from the mid-transverse plane.

Figure 2. The three buckle force transducers insitu attached (from left to right) to the median, ulnar and radial nerves in the axilla.

Figure 3. Schematic of the buckle force transducer with a nerve segment.