Comparison of longitudinal excursion of a nerve-phantom model using quantitative ultrasound imaging and motion analysis system methods: A convergent validity study

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Abstract

Background: Quantitative ultrasound imaging is gaining popularity in research and clinical settings to measure the neuromechanical properties of the peripheral nerves such as their capability to glide in response to body segment movement. Increasing evidence suggests that impaired median nerve longitudinal excursion is associated with carpal tunnel syndrome. To date, psychometric properties of longitudinal nerve excursion measurements using quantitative ultrasound imaging have not been extensively investigated.

Methods: This study investigates the convergent validity of the longitudinal nerve excursion by comparing measures obtained using quantitative ultrasound imaging with those determined with a motion analysis system. A 38-cm long rigid nerve-phantom model was used to assess the longitudinal excursion in a laboratory environment. The nerve-phantom model, immersed in a 20-cm deep container filled with a gelatin-based solution, was moved 20 times using a linear forward and backward motion. Three light-emitting diodes were used to record nerve-phantom excursion with a motion analysis system, while a 5-cm linear transducer allowed simultaneous recording via ultrasound imaging.

Results: Both measurement techniques yielded excellent association ($r=0.99$) and agreement (mean absolute difference between methods = 0.85 mm; mean relative difference between methods = 7.48 %). Small discrepancies were largely found when larger excursions (i.e. > 10 mm) were performed, revealing slight underestimation of the excursion by the ultrasound imaging analysis software.

Conclusion: Quantitative ultrasound imaging is an accurate method to assess the longitudinal excursion of an in vitro nerve-phantom model and appears relevant for future research protocols investigating the neuromechanical properties of the peripheral nerves.

Keywords

Sonography, in vitro, musculoskeletal, physiotherapy, median nerve

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Introduction

In carpal tunnel syndrome (CTS), thickening of synovial tissue within the carpal tunnel, chronic compression and nerve tethering are the known pathological contributors that can lead to adherence of the median nerve.¹ Increasing evidence suggests that the impaired

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median nerve longitudinal excursion is associated with CTS.^{2,3} Nerve-gliding techniques are routinely used in the clinical rehabilitation practice for their potential neuromechanical effects such as peripheral nerve excursion (i.e. gliding) and intraneural tension changes (i.e. tensioning).⁴⁻⁶ Nerve-gliding techniques consist of specific mobilization aiming to take the peripheral nerves across their available range of motion⁷ and could theoretically reduce adhesions and facilitate excursion.^{8,9} Limited evidence is available on the efficacy of the rehabilitation programmes based on the nerve-gliding techniques although potential beneficial effects have been reported in terms of reduced pain intensity,^{10,11} decreased need for surgery,¹² and inhibitory effects pertaining to nociceptive neuronal pool located at the spinal cord level (i.e. dorsal horn neurons).¹³ Surprisingly, no studies have quantified the potential effects of rehabilitation programmes based on the nerve-gliding techniques by directly investigating the biological or neuromechanical property of the nerve despite suggestions emerging from previous studies.^{5,8,12}

The use of quantitative ultrasound imaging (QUI) and advanced image analysis software now enables rehabilitation professionals to acquire additional information for optimal care planning and treatment decisions.¹⁴⁻¹⁶ Nonetheless, measuring longitudinal nerve excursion using real-time ultrasound imaging still remains a challenge since the peripheral nerves are continuous anatomical structures with no definite starting and ending points and have an uncertain dynamic trajectory when body segments are moved.^{17,18} Over the past decade, two image analysis methods with embedded decisional algorithms have been proposed in the literature to quantify the dynamic longitudinal nerve excursion and both have predominantly focused on the median nerve: (1) tracking of tissue speckles within regions of interest (ROI),¹⁶ and (2) use of spectral analysis of the ultrasound pulse repetition frequency variation (i.e. Doppler effect).¹⁹ To date, psychometric properties of longitudinal nerve excursion measurements using QUI have not been extensively investigated, although currently available reports have confirmed excellent reliability and a standard error of measurement (SEM) for the median nerve (SEM = 0.41–1.21 mm; minimal detectable change (MDC) = 0.95–2.82 mm)^{5,20} and sciatic nerve (SEM = 0.09–0.21 mm; MDC = 0.24–0.59 mm).²¹ Furthermore, current studies using this method have also revealed different nerve excursion directions (i.e. caudal and cephalic) when testing different movement combinations linked to nerve-gliding techniques.^{5,22} Yet, the strength of the evidence pertaining to the validity of nerve excursion measures computed with QUI is relatively weak.

To further define the psychometric properties of this method, this study aims to investigate the convergent validity (i.e. association and agreement between measures) between longitudinal nerve-phantom excursion measures computed with QUI analysis software and a motion analysis system (i.e. the gold standard). Good convergent validity is expected between these two methods (correlation between measures ≥ 0.75 ; absolute difference between measures ≤ 0.95 mm).^{5,20}

Methods

Nerve-phantom model

A homemade preparation was made using 28 g of unflavored gelatin (4 packs of Knox brand gelatin) and 10 g of psyllium hydrophilic mucilloid fiber, both dissolved in 500 mL of boiling water, before being placed in a rectangular-shaped cardboard container (8 cm $\times$ 20 cm).²³ For convenience, a commercially available acrylonitrile butadiene styrene rod (cross-sectional area = 18.02 mm²; length = 38 cm) served as the nerve-phantom model given its relative rigidity and echogenic appearance on ultrasound imaging. Once the gelatin-based mixture had set to a gel in the refrigerator, the two extremities of the cardboard were punctured and the rod was carefully introduced into the container via the small holes. Figure 1 provides further assembly details.

Laboratory assessment

One of the investigators manually glided the nerve-phantom model within the gelatin-based mixture to the left ($N=12$ trials) and to the right ($N=8$ trials), by pushing or pulling on the portions of the nerve-phantom model that were not embedded into the gelatin-based mixture, for a total of 20 excursion trials. Nerve-phantom excursions were recorded simultaneously via ultrasound imaging and a three-dimensional motion analysis system. To synchronize acquisition between the two systems, a second investigator applied a “flick” to one end of the nerve phantom. This perturbation was visible on the recordings of both methods and served as the starting point for data analysis.

Quantitative ultrasound imaging system

A video sequence of each longitudinal nerve-phantom excursion was acquired using a frame rate of 24 Hz with an ultrasound system encompassing a 12–5 MHz 55 mm linear array transducer connected to an ultrasound machine (HD11 XE, Philips Medical Systems, Bothell, Washington) (Figure 2). The ultrasound

Figure 1. A schematic of the experimental setup with the ultrasound probe supported over the nerve-phantom model. The nerve-phantom model was aligned with the X' -axis of the calibrated 3D orthogonal coordinate system of the laboratory and the quantitative ultrasound system. The nerve-phantom was manually moved predominantly alongside the X' -axis.

Figure 2. An ultrasound image acquisition of the nerve-phantom model. Note the clear upper and lower margins of the rod (white arrows) approximating the hyperechoic appearance of the epineurium of a peripheral nerve and the internal constitution composed of organized grey shade variation cause by small crack formation within the polymer's matrix.

parameters (i.e. depth = 3 cm, gain = 50; transducer frequency = 12 MHz) remained constant during the experiment. The transducer was properly positioned on the preparation and aligned with the nerve phantom before being secured in place with external supports. Thereafter, all video sequences were uploaded into a

desktop computer and analyzed using an in-house image analysis program developed in MATLAB using the Image Processing Toolbox™ software (The MathWorks Inc., Natick, MA, USA; license R2015a) according the method proposed by Dilley et al.¹⁶ This program relies on a frame-by-frame decisional

algorithm method that records the pixel pattern within three regions of interest (ROIs), manually positioned along the nerve phantom by the investigators, before tracking their displacements between consecutive image frames of a video sequence with a block-matching process. Specifically, these three ROIs were defined along the nerve phantom (proximal, middle and distal portions) and the mean displacement of the three ROIs was computed to quantify the longitudinal nerve excursion of each trial. A video sequence presenting one nerve-phantom glide as well as the displacement of the three ROI required to compute the nerve-phantom excursion using the computer program, is available in the electronic supplementary material (<http://journals.sagepub.com/home/ULT>).

Motion analysis system

During each longitudinal nerve-phantom excursion, the trajectory of three light-emitting diodes attached to either end of the nerve phantom (modeled as a rigid body) was recorded at a sampling frequency of 24 Hz using a three-dimensional motion analysis system within the calibrated frame of reference used to fix the 3D orthogonal coordinate system of the laboratory. This three-dimensional motion analysis system, which combined three synchronized camera units (Model 3020; NDI Technology Inc., Waterloo, ON, Canada), reached an estimated global root mean square error of 0.39 mm. For each trial, light-emitting diode trajectories (i.e. X' -, Y' -, and Z' -axis) were filtered by applying two passes of a nonweighted moving average of $n=40$ points at each sample point “ t ” of the displacement (x). Each pass is equivalent to: $\bar{x}_t = (x_t + x_{t-1} + \dots + x_{t-(n-1)})/n$, where $\bar{x}_t$ and x_t represent the filtered and unfiltered data, respectively. We combined the data of the three light-emitting diodes using the mean of each filtered trajectory. The nerve-phantom model was carefully inserted horizontally and perfectly aligned with the X' -axis of the calibrated 3D orthogonal coordinate system of the laboratory. Moreover, the nerve-phantom model was embedded into the XY plane of the laboratory (i.e. perfect alignment with the sagittal plane). Hence, the longitudinal excursion of the nerve-phantom model, recorded simultaneously with the ultrasound imaging and motion analysis systems, occurred in the same plane of movement in the direction of the X' -axis (Figure 1). Therefore, only the mean of the filtered data obtained in the X' - and Y' -axes served to determine the excursion computed with the motion analysis system. The excursion was determined following the same procedure found in the QUI software using the formula: $\sqrt{(X_i^2 - X_{ii}^2) + (Y_i^2 - Y_{ii}^2)}$, where X_i and

X_{ii} refer to the adjacent displacements obtained in the X' -axis and similarly in the Y' -axis. The total amount of excursion was determined by the summation of the displacement increments.

Data analysis

The strength of the association between the two measurement techniques was determined using a Pearson product-moment correlation coefficient (r); the absolute agreement and the 95% limits of agreement (mean difference $\pm 1.96 \times$ standard deviation of the difference) were calculated according to the method proposed by Bland and Altman.²⁴ We also sought to control for any potential association between the magnitude of differences between the two methods and the velocities of the nerve-phantom excursion and computed a Pearson product-moment correlation coefficient (r) between these two variables. The r values were interpreted according to the following guidelines: poor ($r \leq 0.20$), fair ($r = 0.21-0.40$), moderate ($r = 0.41-0.60$), good ($r = 0.61-0.80$), and very good association ($r = 0.81-1.00$).²⁵ Data were analyzed using SPSS (version 21.0). The level of significance was set at $p < 0.05$.

Results

On average, the mean (SD) nerve excursions computed using the QUI method were 10.91 (4.60) mm or 11.79 (4.47) mm with the motion analysis method. An excellent association ($r = 0.99$; $p < 0.01$) was found for the nerve-phantom longitudinal excursion measures computed with the two methods (Figure 3(a)). The mean absolute difference between the two measurement methods was -0.85 mm (range: -2.40 mm to 0.29 mm) with 95% limits of agreement of -2.33 mm to 0.63 mm (Figure 3(b)). A moderate association between the differences between the two measurement methods and the nerve excursion velocity as measured via ultrasound imaging was found ($r = -0.51$; $p = 0.02$) (Figure 3(c)). Hence, nerve excursion velocity only explains 26.2% (R^2) of the variance observed.

Discussion

The very good association found between the two measurement methods tested in the present study supports the convergent construct validity of the ultrasound imaging and motion analysis system methods used to compute longitudinal excursion of the nerve-phantom model. The mean difference between the longitudinal nerve-phantom excursion (absolute $\Delta = 0.85$ mm; relative $\Delta = 7.48\%$), which does not exceed the MDC value (i.e. 0.95 mm) reported in the literature for the QUI measurement of the median

Figure 3. Scatter plot diagram showing correlation between longitudinal nerve-phantom excursions measured by ultrasound and motion analysis system (a), a Bland-Altman plot with 95% agreement limits (b) and a scatter plot showing correlation between the nerve excursion differences between the two methods (QUI method–motion analysis method) and velocity of the glides (c).

nerve excursion,²⁰ further supports the hypothesis that almost equivalent longitudinal nerve-phantom excursions are computed for the two measurement techniques tested. Hence, the use of QUI for quantifying longitudinal excursion of peripheral nerves (e.g. median nerve) is promising and may prove useful in clinical practice or as part of a research protocols in the future. However, careful interpretation of the measures is warranted when quantifying longitudinal nerve excursion since the QUI-based method often underestimates the longitudinal nerve-phantom excursion compared to the motion analysis system method, mainly when the longitudinal nerve-phantom excursion exceeds 10 mm. Interestingly, studies reporting longitudinal peripheral nerve excursions using the QUI technique have reported excursions < 10 mm when this method of measurement is used, for example, at the median nerve^{26,27} or sciatic nerve.²¹ One potential explanatory factor of the differences computed between methods was investigated (i.e. effect of velocity of the nerve-phantom longitudinal displacement) and was found to have only minimal impact on the differences computed between both methods tested. In fact, a slight tendency for these differences to progress as velocity increases was observed. The results of this study should be weighed in light of the decision to use an artificial nerve model. We acknowledge that the use of an actual median nerve is relevant; however, the nervous tissue's characteristics in situ may be altered when exposed ex vivo such as in the present context. Studies have found that excised nerve show increased compliance due to reduce friction with perineural interface and loss of internal pressure.^{28,29} Future work could aim to define the effects of tensile loading on excursion and elongation within the nerve ex vivo, especially when different loading velocities are applied. Furthermore, the increasingly rapid pace of technology advancements over the past decade in ultrasound imaging system (e.g. spatial compounding) and transducer features (e.g. 3D transducers, high-frequency transducers), alongside the development of new image processing approaches (e.g. harmonic enhancement and adaptive tracking-software), also need consideration. These advancements could strengthen the reliability and validity of QUI measures and lead to development of novel methods to quantify nerve excursion.

Conclusion

Very good association and agreement were confirmed for the longitudinal nerve-phantom excursion measures obtained using the quantitative ultrasound imaging and motion analysis methods. These results support the use of QUI as a relevant approach to assess the neuromechanics properties of the peripheral nerves in future

research protocols. Caution is however warranted if peripheral nerve excursions > 10 cm are encountered as QUI could underestimate the absolute amount of excursion.

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