EPIMUSCULAR MYOFASCIAL FORCE TRANSMISSION BETWEEN NERVE AND MYOTENDINOUS UNIT: A SHEAR-WAVE ELASTOGRAPHY STUDY

Javier Álvarez-González [a,b], Germán Digerolamo [c,d], Nicolás Cuenca-Zaldivar [e,f], Davinia Vicente-Campos [a], Sandra Sánchez-Jorge [a], Elena Keough [g], Andrzej Pilat [c]

[a] Faculty of Health Sciences, Francisco de Vitoria University, Madrid, Spain.
[b] Department of Radiology, Hospital General Universitario Gregorio Marañón, Madrid, Spain.
[c] School of Myofascial Therapies Tupimek, El Escorial, Spain.
[d] Institute of Neuroscience and Physiotherapy, Segovia, Spain.
[e] Department of Nursing and Physiotherapy, Faculty of Medicine and Health Sciences, University of Alcalá, Alcalá de Henares, Spain.
[f] Research Group in Nursing and Health Care, Puerta de Hierro Health Research Institute-Segovia de Arana (IDIPHISA), Madrid, Spain.
[g] Department of Intensive Care Medicine, Hospital Universitario La Princesa, Madrid, Spain.

Corresponding author: Javier Álvarez-González. Faculty of Health Sciences, Francisco de Vitoria University, 28223 Madrid, Spain. Mail: j.alvarezglez.prof@ufv.es. Phone:+34 917 091 400 ext 1955

ABSTRACT

Introduction:

Epimuscular myofascial force transmission can occur bidirectionally between muscles and nerves through a connecting neurovascular tract. The purpose of this study was to determine whether a neurodynamic stress test produces stiffness changes in the adjacent myotendinous complex. The authors also assessed which anatomical variables had an impact on elasticity changes provoked by the maneuver.

Methods:

A convenience sample of healthy adults (n=39) recruited from a university population who met the inclusion criteria participated voluntarily in this study. Using Shear-Wave elastography, stiffness data were obtained for the ulnar nerve, flexor carpi ulnaris tendon and muscle before and after a neural tensioning maneuver.

Results:

Following an ulnar nerve stretch, statistically significant differences were obtained in neural stiffness increase in nerve ($p<0.001$), tendon ($p<0.001$) and muscle ($p=0.046$), with a moderate ($d=0.538$), small ($d=0.485$) and small ($d=0.224$) effect sizes, respectively. The changes obtained were greater in those individuals with a smaller anatomical distance between nerve and tendon.

Conclusions:

Alterations in peripheral neural tissue tension involves elasticity changes in adjacent musculoskeletal tissue mediated by the neurovascular tract. Collateral force transmission was determined by the individual anatomical differences of each subject.

Future research should assess whether the observed increase in myotendinous stiffness due exclusively to the passive transmission of force through the connective bridges between the two tissues studied or if there is a “neuroprotective” muscle contraction following neural stress.

Keywords:

Myofascial force transmission, Shear-Wave elastography, Neurovascular tract, Neurodynamic, Connective tissue.

INTRODUCTION

Muscles are structurally and functionally related to connective tissue. The epimysium surrounds each muscle, connecting with the tendons and periosteum. Perimysium forms muscle fascicles, while endomysium covers each muscle fibre. Functional demands and mechanical forces influence both the quantity and composition of this connective tissue (Purslow, 2020, 2010)

In recent decades, interest in connective tissue has increased due to its role in muscular force transmission (Huijing, 2009), proprioception, and pain perception (Fede et al., 2020; Mense, 2019). The fascia's continuous structure challenges the view of muscles as isolated functional units (Maas, 2019). The neurovascular tract, in its role as a connective tissue, connects muscle to other tissues mechanically (Huijing, 2009; Yucesoy et al., 2010)

The sliding filament theory, introduced over 60 years ago, posits that muscle fibres shorten from end to end as "A" bands come together (Huxley and Niedergerke, 1954). This model suggests longitudinal force transfer via sarcomere shortening. However, a secondary matrix of proteins also transmits force across the muscle fibre to the tendons, protecting fibres from damage. The costamere, part of this matrix, connects the sarcolemma to the contractile apparatus, playing a crucial role in muscle function and injury prevention (Hughes et al., 2015).

Street et al. highlighted in 1983 that skeletal muscle force is transmitted both longitudinally and transversely (Street, 1983).). Longitudinal transmission occurs along the muscle fibre, while collateral pathways transmit force from each sarcomere to the connective tissue and extracellular matrix, then to the tendon (Gao et al., 2014). This collateral force transmission, known as "epimuscular myofascial force transmission (EMFT)" (Huijing, 1999; Yucesoy, 2010), involves transmission from the entire myofibril surface without the direct involvement of the myotendinous/myoaponeurotic unit (Pamuk et al., 2020).

Up to 80% of force transmission is suggested to occur through EMFT (Hughes et al., 2015), underscored by muscular dystrophies like Duchenne muscular dystrophy where protein complexes are altered.

Due to the close morphological relationship between muscles and connective tissue, changes in local stiffness can affect surrounding areas (Wilke et al., 2018). Changing the length of a muscle alters the forces on adjacent muscle tendons that remain unchanged in length. Stretching a muscle affects its tension and that of neighbouring muscles (Yoshitake et al., 2018a).

Intermuscular force transmission also occurs between muscle and other tissues. The neuromuscular tract links the intramuscular connective tissue network with the neurovascular complex support matrix (Maas and Sandercock, 2010).

On another note, peripheral nerves must adapt their length to the stretching and flexing movements of the extremities. They have a complex structure of neuron bundles packed into fascicles, surrounded by connective tissue layers, the perineurium and epineurium (Phillips et al., 2004). Due to these characteristics, they can be subjected to mechanical stress through tension. These manoeuvres, known as "neurodynamic", are used by physiotherapists to evaluate and treat painful musculoskeletal disorders (Boyd et al., 2009).

Neurodynamic assessment has become popular in evaluating and treating neural and musculoskeletal disorders (Shacklock, 2005). Through polyarticular movement, mobilizing the peripheral nervous system applies a mechanical load on neural tissue, altering the length and dimensions of the bed supporting these neurovascular structures, thus improving pain tolerance (Nee and Butler, 2006; Zamorano-Zárate, 2013).

Besides mobilizing neural tissue, peripheral nerves can be "stretched" through precise positioning of the joints that the selected nerve crosses (Martínez et al., 2014). Cadaver studies confirm that neural stretching techniques can increase nerve length (Byl et al., 2002). Likewise, a 65% increase in ulnar nerve strain at the wrist level has been found when performing this maneuver (Wright et al., 2001).

The development of Shear-Wave Elastography (SWE) enables the evaluation of changes in the elastic properties of living tissues. SWE works by analysing the speed at which perpendicular waves are formed as the main ultrasound beam travels through tissue (Brandenburg et al., 2014; Franchi-Abella et al., 2013). The relationship between the mechanical properties of these shear-waves and tissues began being studied in 1960 (Drakonaki et al., 2012; Taljanovic et al., 2017). Since then, studies have shown the relationship between shear-wave speed and tissue stiffness (Guzmán Aroca et al., 2014; Hug et al., 2015).

There is an anatomical continuity of connective tissue between the ulnar nerve and the flexor carpi ulnaris tendon. This fascial connection is referred to as the neurovascular tract. Due to the existence of EMFT, we can assume that an increase in tension in one tissue induced by a maneuver will result in an increase in stiffness in another tissue via the neurovascular tract. These changes can be seen and quantified using SWE.

To our knowledge, there are no "in vivo" studies that demonstrate the changes in elasticity/stiffness of one tissue induced by a change in the stiffness of a different tissue, which could be mediated by the neurovascular tract. Furthermore, the anatomical pathways through which these forces are transmitted may differ for each individual depending on the configuration of their local structure (Grechenig et al., 2001).

The purpose of this study was to observe “in vivo” using SWE whether changes in ulnar nerve tension by means of a neurodynamic maneuver is associated with changes in ulnar flexor muscle and tendon stiffness. Additionally, we aim to determine what anthropometric factors can influence the tension and stiffness caused by this neurodynamic maneuver.

MATERIALS AND METHOD

Sample

Thirty-nine healthy subjects were recruited during the study period who met the inclusion criteria (university students between 18 and 26 years old, right-handed, without any episodes of neck pain the previous year or neuropathies in the upper limb, without trauma or surgery in the neck or upper limb) participated voluntarily in this study, which was approved by the Ethics Committee of the Francisco de Vitoria University (Madrid, Spain) with nº 15/2017 and enrolled in *Clinical Trial* with ID nº NCT03509337. All individuals signed an informed consent prior to their participation.

Procedure

The participants maintained a relaxed position, with minimal tension on the peripheral neural system: supine, head and neck in a neutral position, left hand on the abdomen with legs flexed and supported on a wedge (Zamorano-Zárate, 2013). The right arm was held passively at 30º abduction, elbow in 10º flexion and forearm in 30º supination. Wrist and distal joints held in a relaxed position. This initial position guarantees a relaxed state of the flexor carpi ulnaris muscle (FCUM) and its tendon (FCUT) as well as the ulnar nerve (UN), which was confirmed by asking the patient for their perception. The lack of sensation of tension in the upper limb confirmed the correct initial position. To put tension on the UN without affecting the length of the FCUM (insertion in pisiform, hamate and base of the 5th metacarpal) or its tendon, an expert researcher in neural tissue mobilization with over 10 years of experience performed extension of the 4th and 5th metacarpophalangeal joints and corresponding distal joints. The other joints were maintained without changes until an exponential increase in resistance of the tissues placed under tension was perceived (Kwan et al., 1992). The participants also verbalized the moment which they felt the increase in tension. Both the start and end positions are shown in figure 1.

Ultrasound and Shear-Wave Elastography

A Canon TUS Ai800 (Aplio i800) ultrasound machine fitted with a PLT-1005BT 14L5 multi-frequency linear probe (5-14 MHz) and Shear-Wave elastography software (Canon Medical Systems, Japan) was used. The researcher in charge of the ultrasound has over 10 years of experience in musculoskeletal studies.

With the participant in the initial resting position, an image was obtained in a transverse plane 5 cm proximal to the pisiform bone in which the structures of interest for this study were identified (ulnar nerve, flexor carpi ulnaris muscle and tendon) using 2D ultrasound mode and color Doppler (figure 2A). The ultrasound parameters (depth, focal position, gain, and dynamic range) were adjusted to obtain a high-quality image that allows for the unequivocal identification of the structures of interest for this study. The images were stored for later analysis. Images of the same structures were then obtained in the longitudinal plane (figure 2B), on which the SWE study was then performed. These measurements are performed in the longitudinal plane because of the anisotropic properties of the neurovascular and musculoskeletal tissues (Dubois et al., 2015; Lee et al., 2016; Miyamoto et al., 2015).

The colour scale extremes were adjusted for each tissue and each participant to obtain a high-quality elastogram that allowed for the proper positioning of the ROIs in the selected locations. As long as the area to be quantified (the location of the ROIs) is covered by colour, modifying the colour scale does not alter the shear wave velocity values and, therefore, the stiffness measured in kilopascals. Colour void areas, whether due to excess or deficiency, are beyond the software's reading capacity.

Three Regions of Interest (ROI) adjacent to each other were established on the obtained elastogram, each one covering the total diameter of the ulnar nerve. The stiffness measurements obtained were recorded in Kilopascals (KPa) (figure 3). FCUM and FCUT tension measurements were also obtained using a ROI size determined by the diameter of the nerve that was first explored.

The same procedure for obtaining elastography data was repeated in the final position with neural tension in order to compare the pre / post tension data.

Anatomical relation of adjacent structures

The anatomical location of the neurovascular bundle and its relationship with the flexor carpi ulnaris tendon was visually analyzed. Those individuals in whom both adjacent elements were identified and only separated by a connective tissue interface were grouped under the term "wall-to-wall". Meanwhile, those in which a connecting neurovascular tract of more than 4mm was identified were termed "distant neighbors." Figure 4 illustrates this classification, which is due to the individuality of each patient and their anatomical variations (Kachare et al., 2020; Lung y Siwiec, 2020).

Data and statistical analysis

The R Ver. 3.3.3. was used for the statistical analysis (R Foundation for Statistical Computing, Institute for Statistics and Mathematics, Welthandelsplatz 1, 1020 Vienna, Austria). The level of significance was established at $p < 0.05$. The distribution of quantitative variables was tested with the Shapiro-Wilk, which showed how the majority had a non-normal distribution. Quantitative variables were described with median [interquartile range] or mean ± standard deviation depending on its distribution. Qualitative variables were expressed with absolute and relative frequencies. The Wilcoxon Signed-Rank test was applied between pre-test/post-test outcome variables and the U Mann-Whitney test between outcome and baseline variables. The effect size (Cohen's d) was defined as not relevant (<0.20), small (between 0.20 and 0.50), moderate (between 0.50 and 0.80), or large (≥0.80). Minimal Detectable Change (MDC) was also calculated for pre-postest outcome variables.

RESULTS

39 healthy subjects were recruited, 17 men and 22 women of 20.69±2.20 years with a BMI of 21.56±2.90 considered as healthy status (Table 1).

The stiffness of the tissues was compared at rest versus the moment when the participants reported a sensation of tension. Pre-test/post-test outcome variables showed significant differences in the ulnar nerve ($Z=4.7589$, $p<0.001$) with an increase of 39 KPa and a moderate effect size. In the ulnar tendon ($Z=4.2918$, $p<0.001$) the stiffness values increased by 27 KPa with a small effect size and, in the case of the flexor carpi ulnaris muscle, there was a significant (Z=1.9828, p=0.046) increase of 3 KPa with a small effect size (Table 2).

The Mann-Whitney U test showed that neural tensioning caused a greater increase in tendon stiffness in the “wall-to-wall” group than in the “distant neighbors” group (53.5 KPa and 12 KPa respectively. P <0.05). Tension changes in nerve or muscle were not statistically significant. There were no significant differences in the other variables analyzed. MDCs are very high indicating a low sensitivity to change.

DISCUSSION

The results of our study confirm that there is evidence of a transmission of forces between different tissues. Specifically, an increase in stiffness within the myotendinous unit is evidenced following an increase in tension of the adjacent neural tissue. In accordance with other authors, the neurovascular tract seems to be the route of lateral force transmission (Huijing, 2009).

Previous studies in animal models have been able to successfully predict the amount of EMFT under different experimental conditions (Bernabei et al., 2016). Other researchers (Freitas et al., 2019; Yoshitake et al., 2018b) showed the existence of EMFT mediated by collagen bonds between the epimysium of adjacent muscles, as well as by the presence of the neurovascular tract. The authors demonstrated tension changes induced within a muscle during the relative stretching of an adjacent muscle. Similarly, there is evidence of EMFT in synergistic and antagonist muscles in patients with cerebral palsy (Kaya et al., 2020).

However, our study has confirmed that this transmission of forces also occurs between different tissues. More specifically, force transmission is seen between muscles, tendons and neural tissue. This transmission is mediated by the presence of the neurovascular tract (Huijing, 2009), which serves as a link between the different tissues, as can be seen in ultrasound images obtained.

The muscle offers less resistance to elongation than nerves and tendons, so generating neural elongation increases the stiffness of both this tissue and the tendon, as we have shown in the study; however, the muscle modifies its stiffness to a lesser extent, relative to its intrinsic mechanical properties, which are very different from those of the other two tissues studied (Feng et al., 2018). On the other hand, the slight increase observed could be due to a "neuroprotective" contraction. The reason for this slight increase in stiffness should be addressed by future studies specifically designed to answer this question.

The morpho-functional union described supports observations made in spastic patients in whom tenotomy was performed in order to return the wrist and hand to a functional position. This procedure failed to reverse the flexion seen in spastic ulnar deviation (Smeulders y Kreulen, 2007). The authors of this study observed "*in vivo*" that the neurovascular tissue of the ulnar nerve was connecting and, therefore, possibly triggering the displacement of the proximal end of the severed tendon during passive wrist flexion and extension movements performed "*in situ*".

In addition, increase in myotendinous stiffness in the flexor carpi ulnaris is observed when applying physical stress (stretching) to the ulnar nerve. This may be due to either simultaneous stretching or to a neuroprotective contraction of the muscle.

From a clinical point of view, further research is needed to reveal if the presence of the neurovascular tract serves exclusively as a passive route of transmission of forces or plays a more active role. Studies looking at electromyographic recordings of median nerve tension tests reveal the activity of the arm muscles, which show the appropriate biomechanical conditions to resist stretching of the median nerve (Jaberzadeh et al., 2005). It is important to point out that the activity of these muscles precedes the moment in which the examined individuals report painful sensations. This means that there is muscle activity caused by neural stretching outside of the pain range. It seems that the presence of mechanoreceptors in the connective structures of the nerves would justify the fact that the stretching of the nerve triggers a reflex muscle contraction of certain muscle groups, in a sequenced way and in relation to different ranges of motion.

A greater transmission of forces was observed in the participants with the “wall-to-wall” morphology in contrast to the reduction in force transmission seen in those with the “distant neighbors” type morphology. This may be explained by the inverse square law formulated by Sir Isaac Newton. This law states that an object (in our study a tendon) distant to the origin of a mechanical stimulus (for example the stretching of the ulnar nerve) will perceive said stimulus four times less if the distance from that mechanical stimulus is doubled. In living tissues such as those discussed here, however, biophysical aspects inherent to each participant should be considered, such as viscoelasticity or hydration, which could also affect the muscular response obtained (Denslow, 2000). Studying these factors are beyond the objectives initially set for this study but could be considered as possible limitations. Deeper anatomical studies could provide further information related to the EMFT and intersubject variability.

However, this anatomical configuration and the tension changes obtained in our study could partly explain the different clinical behavior and therapeutic response to the same mobilization or neural stretching maneuver performed in patients with different clinical conditions, who show different degrees of mechanosensitive (Denslow, 2000; Schmid et al., 2009; Szikszay et al., 2018).

Finally, our study has some limitations, as detailed below: Sample size was determined for convenience. Electromyography was not used to ensure muscle silence in the resting position. Having only one investigation group does not allow for understanding individual or natural stiffness variations or measurement errors.

Subsequent studies with a larger sample could be useful to advance the degree of understanding of the functional aspects of fascial tissue and, specifically, of the neurovascular tract.

CONCLUSIONS

The modification of stiffness in peripheral neural tissue also involves tension changes in adjacent musculoskeletal tissue mediated by the neurovascular tract. The amount of lateral force transmission is related to the anatomical characteristics of the individual.

CLINICAL RELEVANCE

1. Neuromuscular tract plays an important role in the transmission of forces between different tissues.
2. Anatomical particularities of each subject confer different degrees of force transmission between different tissues.
3. Shear-Wave Elastography is an effective tool for demonstrating changes in tissue stiffness under stress by therapists.

Clinical Trial Registration number

NCT03509337

Ethical Approval:

This study was approved by the Ethics Committee of the Francisco de Vitoria University (Madrid, Spain) with nº 15/2017.

Funding:

Any funding was received for the realization of this study.

Declaration of competing interest:

Authors declare no conflict of interest.

ACKNOWLEDGEMENTS

We would like to thank Javier Moreno (Canon Medical Spain, ultrasound division), for the technology provided for the performance of Shear-Wave Elastography. Also, to all the students of the Francisco de Vitoria University who participated as volunteers in this study. Adelaida M. Castro (University of Jaén) made valuable comments on the initial text. Alfredo Bravo-Sánchez (Francisco de Vitoria University) independently reviewed the final manuscript.

REFERENCES

Bernabei, M., Maas, · Huub, Van Dieën, J.H., 2016. A lumped stiffness model of intermuscular and extramuscular myofascial pathways of force transmission. Biomech. Model. Mechanobiol. 15, 1747-1763. https://doi.org/10.1007/s10237-016-0795-0

Boyd, B.S., Wanek, L., Gray, A.T., Topp, K.S., 2009. Mechanosensitivity of the lower extremity nervous system during straight-leg raise neurodynamic testing in healthy individuals. J. Orthop. Sports Phys. Ther. 39, 780-790. https://doi.org/10.2519/jospt.2009.3002

Brandenburg, J.E., Eby, S.F., Song, P., Zhao, H., Brault, J.S., Chen, S., An, K.N., 2014. Ultrasound elastography: The new frontier in direct measurement of muscle stiffness. Arch. Phys. Med. Rehabil. 95, 2207-2219. https://doi.org/10.1016/j.apmr.2014.07.007

Byl, C., Puttlitz, C., Byl, N., Lotz, J., Topp, K., 2002. Strain in the median and ulnar nerves during upper-extremity positioning. J. Hand Surg. Am. 27, 1032-1040. https://doi.org/10.1053/jhsu.2002.35886

Denslow, S., 2000. Constraints on cardiac hypertrophy imposed by myocardial viscosity. J. Appl. Physiol. 89, 1022-1032. https://doi.org/10.1152/jappl.2000.89.3.1022

Drakonaki, E.E., Allen, G.M., Wilson, D.J., 2012. Ultrasound elastography for musculoskeletal applications. Br. J. Radiol. 85, 1435-1445. https://doi.org/10.1259/bjr/93042867

Dubois, G., Kheireddine, W., Vergari, C., Bonneau, D., Thoreux, P., Rouch, P., Tanter, M., Gennisson, J.L., Skalli, W., 2015. Reliable Protocol for Shear Wave Elastography of Lower Limb Muscles at Rest and During Passive Stretching. Ultrasound Med. Biol. 41, 2284-2291. https://doi.org/10.1016/j.ultrasmedbio.2015.04.020

Fede, C., Porzionato, A., Petrelli, L., Fan, C., Pirri, C., Biz, C., De Caro, R., Stecco, C., 2020. Fascia and soft tissues innervation in the human hip and their possible role in post-surgical pain. J. Orthop. Res. 38, 1646-1654. https://doi.org/10.1002/jor.24665

Feng, Y.N., Li, Y.P., Liu, C.L., Zhang, Z.J., 2018. Assessing the elastic properties of skeletal muscle and tendon using shearwave ultrasound elastography and MyotonPRO. Sci. Reports 2018 81 8, 1-9. https://doi.org/10.1038/s41598-018-34719-7

Franchi-Abella, S., Elie, C., Correas, J.M., 2013. Ultrasound elastography: Advantages, limitations and artefacts of the different techniques from a study on a phantom. Diagn. Interv. Imaging 94, 497-501. https://doi.org/10.1016/j.diii.2013.01.024

Freitas, S.R., Antunes, A., Salmon, P., Mendes, B., Firmino, T., Cruz-Montecinos, C., Cerda, M., Vaz, J.R., 2019. Does epimuscular myofascial force transmission occur between the human quadriceps muscles in vivo during passive stretching? J. Biomech. 83, 91-96. https://doi.org/10.1016/j.jbiomech.2018.11.026

Gao, Y., Liu, S., Huang, J., Guo, W., Chen, J., Zhang, L., Zhao, B., Peng, J., Wang, A., Wang, Y., Xu, W., Lu, S., Yuan, M., Guo, Q., 2014. The ECM-cell interaction of cartilage extracellular matrix on chondrocytes. Biomed

Res. Int. 2014. https://doi.org/10.1155/2014/648459

Grechenig, W., Clement, H., Egner, S., Tesch, N.P., Weiglein, A., Peicha, G., 2001. Musculo-tendinous junction of the flexor carpi ulnaris muscle. An anatomical study. Surg. Radiol. Anat. 22, 255-260. https://doi.org/10.1007/S00276-000-0255-4/METRICS

Guzmán Aroca, F., Abellán Rivera, D., Reus Pintado, M., 2014. La elastografía: una nueva aplicación de la ecografía. ¿Cuál es su utilidad clínica? Radiologia 56, 290-294. https://doi.org/10.1016/j.rx.2012.09.006

Hug, F., Tucker, K., Gennisson, J.L., Tanter, M., Nordez, A., 2015. Elastography for Muscle Biomechanics: Toward the Estimation of Individual Muscle Force. Exerc. Sport Sci. Rev. 43, 125-133. https://doi.org/10.1249/JES.0000000000000049

Hughes, D.C., Wallace, M.A., Baar, K., 2015. Effects of aging, exercise, and disease on force transfer in skeletal muscle. Am J PhysiolAmerican J. Physiol. - Endocrinol. Metab. 309, E1-E10. https://doi.org/10.1152/ajpendo.00095.2015

Huijing, P.A., 2009. Epimuscular myofascial force transmission: A historical review and implications for new research. International society of biomechanics Muybridge award lecture, Taipei, 2007. J. Biomech. 42, 9-21. https://doi.org/10.1016/j.jbiomech.2008.09.027

Huijing, P.A., 1999. Muscle as a collagen fiber reinforced composite: A review of force transmission in muscle and whole limb. J. Biomech. 32, 329-345. https://doi.org/10.1016/S0021-9290(98)00186-9

Huxley, A.F., Niedergerke, R., 1954. Structural changes in muscle during contraction: Interference microscopy of living muscle fibres. Nature 173, 971-973. https://doi.org/10.1038/173971a0

Jaberzadeh, S., Scutter, S., Nazeran, H., 2005. Mechanosensitivity of the median nerve and mechanically produced motor responses during Upper Limb Neurodynamic Test 1. Physiotherapy 91, 94-100. https://doi.org/10.1016/j.physio.2004.09.021

Kachare, S.D., Meredith, L.T., Kachare, M.D., Vivace, B.J., Kapsalis, C.N., Muresan, C., Choo, J.H., Kasdan, M.L., Wilhelmi, B.J., 2020. Surface Landmarks to Provide a Safe Ulnar Nerve Block in the Wrist: Anatomical Study and Literature Review. Eplasty 20.

Kaya, C.S., Bilgili, F., Akalan, N.E., Yucesoy, C.A., 2020. Intraoperative testing of passive and active state mechanics of spastic semitendinosus in conditions involving intermuscular mechanical interactions and gait relevant joint positions. J. Biomech. 103, 109755. https://doi.org/10.1016/j.jbiomech.2020.109755

Kwan, M.K., Wall, E.J., Massie, J., Garfin, S.R., 1992. Strain, stress and stretch of peripheral nerve rabbit experiments in vitro and in vivo. Acta Orthop. 63, 267-272. https://doi.org/10.3109/17453679209154780

Lee, S.S.M., Gaebler-Spira, D., Zhang, L.Q., Rymer, W.Z., Steele, K.M., 2016. Use of shear wave ultrasound elastography to quantify muscle properties in cerebral palsy. Clin. Biomech. 31, 20-28. https://doi.org/10.1016/j.clinbiomech.2015.10.006

Lung, B.E., Siwiec, R.M., 2020. Anatomy, Shoulder and Upper Limb, Forearm Flexor Carpi Ulnaris Muscle, StatPearls. StatPearls Publishing.

Maas, H., 2019. Significance of epimuscular myofascial force transmission under passive muscle conditions. J. Appl. Physiol. 126, 1465-1473. https://doi.org/10.1152/japplphysiol.00631.2018

Maas, H., Sandercock, T.G., 2010. Force Transmission between Synergistic Skeletal Muscles through Connective Tissue Linkages. J. Biomed. Biotechnol. 2010, 575672. https://doi.org/10.1155/2010/575672

Martínez, M.D.A., Cubas, C.L., Girbés, E.L., 2014. Ulnar nerve neurodynamic test: Study of the normal sensory response in asymptomatic individuals. J. Orthop. Sports Phys. Ther. 44, 450-456. https://doi.org/10.2519/jospt.2014.5207

Mense, S., 2019. Innervation of the thoracolumbar fascia. Eur. J. Transl. Myol. 29, 151-158. https://doi.org/10.4081/ejtm.2019.8297

Miyamoto, N., Hirata, K., Kanehisa, H., Yoshitake, Y., 2015. Validity of Measurement of Shear Modulus by Ultrasound Shear Wave Elastography in Human Pennate Muscle. PLoS One 10, e0124311. https://doi.org/10.1371/journal.pone.0124311

Nee, R.J., Butler, D., 2006. Management of peripheral neuropathic pain: Integrating neurobiology, neurodynamics, and clinical evidence. Phys. Ther. Sport 7, 36-49. https://doi.org/10.1016/j.ptsp.2005.10.002

Pamuk, U., Cankaya, A.O., Yucesoy, C.A., 2020. Principles of the Mechanism for Epimuscular Myofascial Loads Leading to Non-uniform Strain Distributions Along Muscle Fiber Direction: Finite Element Modeling. Front. Physiol. 11, 1-15. https://doi.org/10.3389/fphys.2020.00789

Phillips, J.B., Smit, X., De Zoysa, N., Afoke, A., Brown, R.A., 2004. Peripheral nerves in the rat exhibit localized heterogeneity of tensile properties during limb movement. J. Physiol. 557, 879-887. https://doi.org/10.1113/jphysiol.2004.061804

Purslow, P.P., 2020. The Structure and Role of Intramuscular Connective Tissue in Muscle Function. Front. Physiol. 11, 519145. https://doi.org/10.3389/FPHYS.2020.00495/BIBTEX

Purslow, P.P., 2010. Muscle fascia and force transmission. J. Bodyw. Mov. Ther. 14, 411-417. https://doi.org/10.1016/j.jbmt.2010.01.005

Schmid, A.B., Brunner, F., Luomajoki, H., Held, U., Bachmann, L.M., Künzer, S., Coppieters, M.W., 2009. Reliability of clinical tests to evaluate nerve function and mechanosensitivity of the upper limb peripheral nervous system. BMC Musculoskelet. Disord. 10, 11. https://doi.org/10.1186/1471-2474-10-11

Shacklock, M., 2005. Clinical Neurodynamic: A new system of musculoskeletal treament. Butterworth-Heinemann, Edinburgh.

Smeulders, M.J.C., Kreulen, M., 2007. Myofascial force transmission and tendon transfer for patients suffering from spastic paresis: A review and some new observations. J. Electromyogr. Kinesiol. 17, 644-656. https://doi.org/10.1016/j.jelekin.2007.02.002

Street, S.F., 1983. Lateral transmission of tension in frog myofibers: A myofibrillar network and transverse cytoskeletal connections are possible transmitters. J. Cell. Physiol. 114, 346-364. https://doi.org/10.1002/jcp.1041140314

Szikszay, T.M., Luedtke, K., Harry, P., 2018. Increased mechanosensivity of the greater occipital nerve in subjects with side-dominant head and neck pain – a diagnostic case-control study. https://doi.org/10.1080/10669817.2018.1480912

Taljanovic, M.S., Gimber, L.H., Becker, G.W., Latt, L.D., Klauser, A.S., Melville, D.M., Gao, L., Witte, R.S., 2017. Shear-Wave Elastography: Basic Physics and Musculoskeletal Applications. RadioGraphics 37, 855-870. https://doi.org/10.1148/rg.2017160116

Wilke, J., Schleip, R., Yucesoy, C.A., Banzer, W., 2018. Not merely a protective packing organ? A review of fascia and its force transmission capacity. J. Appl. Physiol. 124, 234-244. https://doi.org/10.1152/japplphysiol.00565.2017

Wright, T.W., Glowczewskie, F., Cowin, D., Wheeler, D.L., 2001. Ulnar nerve excursion and strain at the elbow and wrist associated with upper-extremity motion. J. Hand Surg. Am. 26A, 655-662. https://doi.org/10.1016/j.jhsa.2005.06.008

Yoshitake, Y., Uchida, D., Hirata, K., Mayfield, D.L., Kanehisa, H., 2018a. Mechanical interaction between neighboring muscles in human upper limb: Evidence for epimuscular myofascial force transmission in humans. J. Biomech. 74, 150-155. https://doi.org/10.1016/j.jbiomech.2018.04.036

Yoshitake, Y., Uchida, D., Hirata, K., Mayfield, D.L., Kanehisa, H., 2018b. Mechanical interaction between neighboring muscles in human upper limb: Evidence for epimuscular myofascial force transmission in humans. J. Biomech. 74, 150-155. https://doi.org/10.1016/j.jbiomech.2018.04.036

Yucesoy, C.A., 2010. Epimuscular myofascial force transmission implies novel principles for muscular mechanics. Exerc. Sport Sci. Rev. 38, 128-134. https://doi.org/10.1097/JES.0b013e3181e372ef

Yucesoy, C.A., Baan, G., Huijing, P.A., 2010. Epimuscular myofascial force transmission occurs in the rat between the deep flexor muscles and their antagonistic muscles. J. Electromyogr. Kinesiol. 20, 118-126. https://doi.org/10.1016/j.jelekin.2008.09.012

Zamorano-Zárate, E., 2013. Movilización neuromeníngea. Tratamiento de los trastornos mecanosensitivos del sistema nervioso. Panamericana.

TABLES AND ILUSTRATIONS

Table 1

TABLE 1: Clinical and demographic baseline characteristics.

n		**39**
Age		21 [19, 22]
Gender, n(%)	Female	22 (56.4)
	Male	17 (43.6)
Weight		63.72±12.42
Height		170.90±9.94
BMI		20.83 [19.76, 22.69]
Physical Activity, n(%)	Active	26 (66.7)
	Sedentary	13 (33.3)
Schedule, n(%)	Afternoon	18 (46.2)
	Morning	21 (53.8)
Regional morphology	Wall-to-wall	18 (46.2%)
	Distant neighbors	21 (53.8%)

Table 2

Table 2: Pre-test / post-test outcome variables

	Pretest (KPa)	**Postest (KPa)**	**Difference (95%CI)**	**^{a}p value**	**Cohen´s d**	**MDC**
nerve	62 [45.5, 74]	101 [80, 126]	39 (29.999-52.5)	<0.001	0,538	65,821
tendon	107 [91, 129]	134 [109.5, 175]	27 (15.999-39)	<0.001	0,485	98,906
muscle	16 [14.5, 19.5]	19 [13, 27.5]	3 (0.0008-5.499)	0,046	0,224	37,848

MDC: Minimal Detectable Change

Fig. 1


A
B
C

Fig. 2

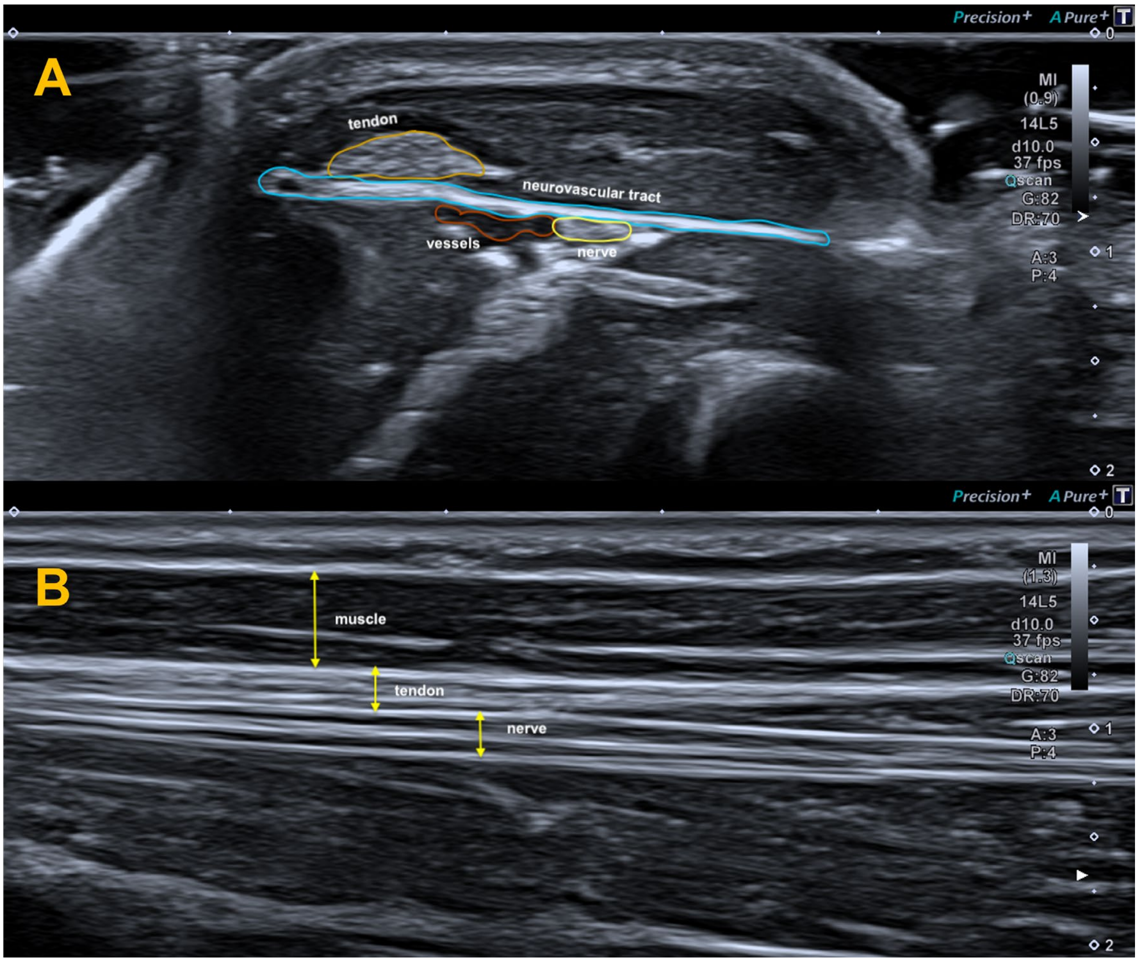

A
tendon
neurovascular tract
vessels
nerve
Precision+
APure+
MI
(0.9)
14L5
d10.0
37 fps
Qscan
G:82
DR:70
A:3
P:4
0
1
2
B
muscle
tendon
nerve
MI
(1.3)
14L5
d10.0
37 fps
Qscan
G:82
DR:70
A:3
P:4

Fig. 3

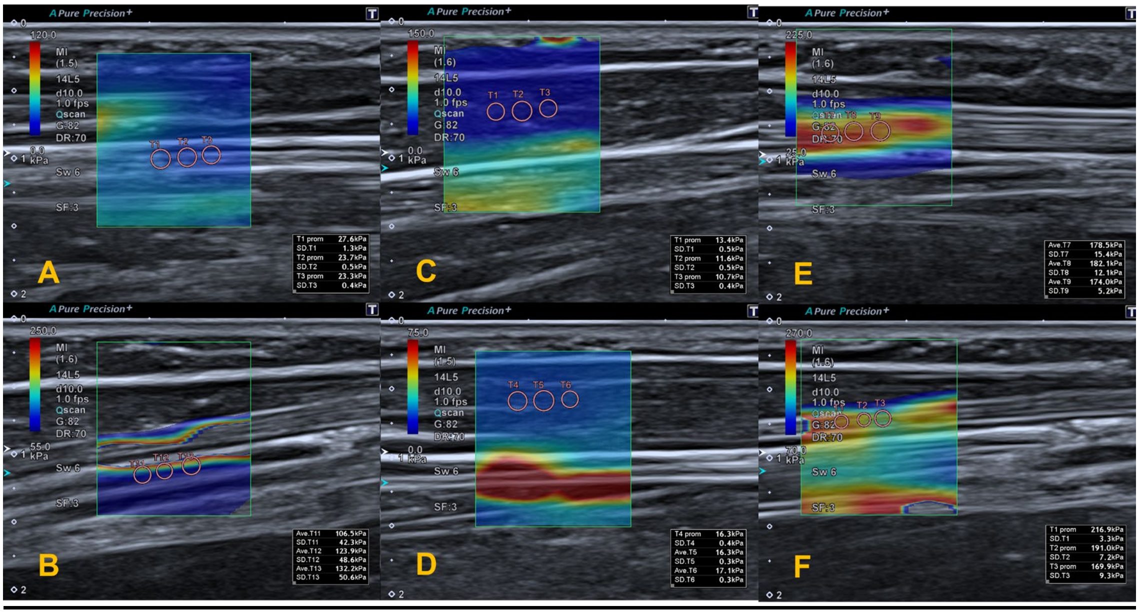
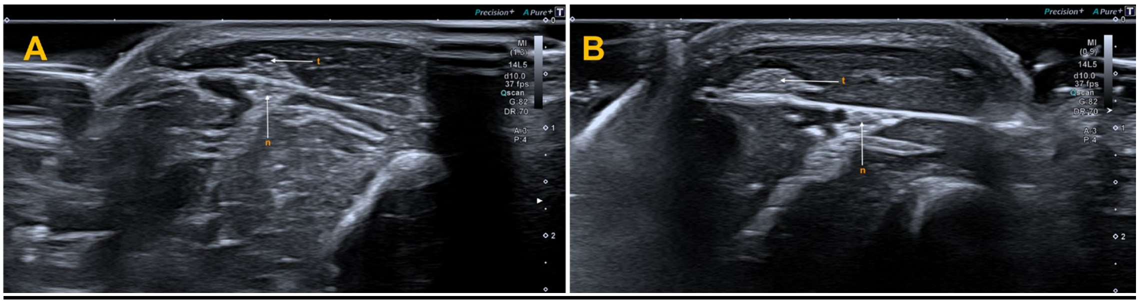

A
T1 prom 27.6kPa
SD.T1 1.3kPa
T2 prom 23.7kPa
SD.T2 0.5kPa
T3 prom 23.3kPa
SD.T3 0.4kPa
C
T1 prom 13.4kPa
SD.T1 0.5kPa
T2 prom 11.6kPa
SD.T2 0.5kPa
T3 prom 10.7kPa
SD.T3 0.4kPa
E
Ave.T7 178.5kPa
SD.T7 15.4kPa
Ave.T8 182.1kPa
SD.T8 12.1kPa
Ave.T9 174.0kPa
SD.T9 5.2kPa
B
Ave.T11 106.5kPa
SD.T11 42.3kPa
Ave.T12 123.9kPa
SD.T12 48.6kPa
Ave.T13 132.2kPa
SD.T13 50.6kPa
D
T4 prom 16.3kPa
SD.T4 0.4kPa
Ave.T5 16.3kPa
SD.T5 0.3kPa
Ave.T6 17.1kPa
SD.T6 0.3kPa
F
T1 prom 216.9kPa
SD.T1 3.3kPa
T2 prom 191.0kPa
SD.T2 7.2kPa
T3 prom 169.9kPa
SD.T3 9.3kPa

Fig. 4


A
t
n
B
t
n

CAPTIONS TO TABLES AND ILUSTRATIONS

Table 1: Clinical and demographic baseline characteristics.

Data expresed with median [interquartile range] or mean±standard deviation and with absolute and relative values (%).

Table 2: Pre-test / post-test outcome variables.

Data expressed as median [interquartile range]. 95%CI: 95% confidence interval. [a]significant if $p<0.05$.

Fig. 1: Ulnar nerve tension maneuver and positioning of the ultrasound probe for the acquisition of elastographic images. **(A)** Overview of the patient's starting position. **(B)** Initial position of the carpal and distal joints, with the relaxed position of the 4th and 5th fingers. **(C)** Final position of the wrist and fingers applying ulnar nerve tension without affecting the length of the flexor carpi ulnaris muscle.

Fig. 2: Initial ultrasound images. **(A)** Cross-sectional image showing the anatomical relationship between the vascular structures, ulnar nerve, flexor carpi ulnaris muscle and tendon, and the neurovascular tract connecting them. **(B)** Longitudinal plane of the ulnar nerve, flexor carpi ulnaris muscle and tendon.

Fig. 3: Shear-Wave Elastography in the longitudinal plane and the average data obtained in Kilopascals (KPa) of the different ROIs. **(A)** Ulnar nerve in the initial resting position. **(B)** Ulnar nerve at the end of the tensioning manoeuvre. **(C)** Flexor carpi ulnaris muscle at rest. **(D)** Flexor carpi ulnaris muscle at the end of the neural tensioning manoeuvre. **(E)** Carpi ulnaris tendon in the initial position. **(F)** Carpi ulnaris tendon in the nerve tensioning position.

Fig. 4: Regional anatomy seen in 2D ultrasound mode in a transverse plane 5 cm proximal to the pisiform bone. t = flexor carpi ulnaris tendon. n = ulnar nerve. **(A)** Regional “wall-to-wall” anatomy; Note that the fascia that constitutes the neurovascular tract is the only structure providing direct contact between the tendon and nerve. **(B)** Regional anatomy of the “distant neighbors” type; both structures are distant from each other and connected through the neurovascular tract.