

3dEnergy Percussion Therapy White Paper

Dr Nicholas Hodgson, B.App.Sc.(Chiropractic)

Email: drnick@superhealthy.com.au

Website: www.superhealthy.com.au



A new model and modality for the management of spinal subluxation

Percussion massage guns are used by athletes, fitness enthusiasts, coaches and trainers and a variety of health professionals with the goals of decreasing pain, reducing soreness, relieving discomfort, increasing flexibility and range of motion, hastening post exercise recovery, assisting with warm-up regimes, perhaps augmenting performance, and for relaxation. There is sufficient evidence to support the strength of each of these outcomes.

One of Chiropractic's unique propositions is in regards to the spinal subluxation. A significant portion of the Chiropractic profession sees its primary focus to differentially diagnose the site, biomechanical nature, and neurological manifestations of each person's subluxation pattern/s. The therapeutic goal is to remove/improve the signs of subluxation in order to improve local function and varying degrees of quality of life and holistic wellbeing.

In addition, many Chiropractors also see it as their role to improve neuromusculoskeletal health, and often integrate multiple therapeutic modalities in order to assist their patients with different dimensions of functional impairment.

The author of this paper and co-developer of the 3dEnergy gun (an evolution in the design of a professional quality percussion massage gun) proposes that the modifications made to this particular percussion instrument, bridge the gap between the use of this machine to treat myofascial soft tissues alone, through to an ideal tool to assist with the correction of the manifestations of spinal subluxation.

The perceived upgrades that were identified for this purpose were:

- To modify and customise the gun head tip composition to allow the delivery of localized specific impulses into hard contacts (cranial bones, vertebral spinous and transverse/lamina processes, pelvic and other joint margins). An airbag configuration was determined to be the only effective design. The shape, density and dimensions were refined to achieve the goal of being able to stimulate specific neurological segments.
- To invent an add-on rotating head component, which would allow the chiropractor to deliver the 3d components of a vertebral subluxation listing (rotation with superiority or inferiority, or in other words the coupled movements that exist in spinal motion patterns). A number of models were developed and tested to finally produce an add-on head component which could develop sufficient torque while maintaining machine balance and smooth harmonics.
- To redesign the internal engineering of the gun to be able to deliver power and controls to the rotating head component, and offer the user a variety of settings for optimal therapeutic choices.

A two-year design and development phase has now been completed.

This means that the 3dEnergy gun can be used as:

- A conventional percussion massage gun.
- The rotating head can be added to increase therapeutic impact on myofascial tissues.
- Or, as hoped, it can additionally be used to deliver the required correctional vectors to help with subluxation management.

Working hypotheses:

1. That percussive therapy is an ideal choice for the management of subluxation, based on its potential to impact each of the five components of subluxation: Impulse force delivered into a correctional vector and vibration to positively impact kinesio pathology; Energetic biodynamic transmission to positively impact neuropathophysiology; Percussion to positively impact myopathology; Hyperaemic response to positively impact histopathology; and a combination of all of the above to positively impact pathophysiology.
 2. That the appropriate delivery of percussive impulses to selected neural levels of the spinal system will act to clear dysfunctional ascending neural gateways, leading to improved central and peripheral neural function and the positive wellbeing outcomes associated with this.
 3. That percussive therapy is suited to delivering therapeutic mobilisation to the tensegrity components of the neuromusculoskeletal system.
 4. That percussive therapy is a suitable mechanical and energetic intervention to impact the effects of subluxation on the cranio-spinal-functional-meningeal-unit (CSFMU) via spinal to meningeal fibrous attachments.
 5. That the energetics of percussive therapy is suited to intervening positively into the piezoelectric properties of the fascial, spinal and central nervous systems.
- **All of the above can be encapsulated by one term – MECHANOTRANSDUCTION – the mechanisms by which cells convert mechanical stimuli into electrochemical activity.**

Force and frequency settings of the 3dEnergy Gun:

Percussion					Rotation	
Button press #	Ampl (mm)	Freq (Hz)	Force (Newtons)	Force (lbf)	Button press #	RPM
1	10	25	66.7	15	1	20
2	10	30	111.2	25	2	25
3	10	35	146.8	33	3	30
4	10	40	169.0	38	4	0
5	10	45	191.3	43		
6	10	50	213.5	48		
7	0	0	0	0		

The 6 'Ys' of health and quality of life

1. Adaptability
 - The quality of being able to adjust to new conditions.
 - In university we are taught all about homeostasis and how it is the maintenance of a stable internal physiological environment which keeps us alive in a continuously and at times dramatically changeable environment.
 - So, here's the paradox – to maintain homeostasis requires massive potential for adaptability from every physiological system. There is no homeostasis without constant change!
 - This necessity exists in every single functional capacity.
 - In terms of the neuromusculoskeletal system examples of adaptability are:
 - a. Maintaining balance against the effects of gravity.
 - b. Maintaining ideal posture.
 - c. Balance and coordination of movement patterns.

2. Flexibility

- The ability to move through an unrestricted range of motion.
- There is a range of motion in every capacity to adapt, and that range can be diminished or increased in varying states of health.
- Eg. There is capacity to how hot or how cold an environment we can survive in. But the end points of these extremes can vary between individuals depending on their own ability to adapt to the extremes.
- In terms of the neuromusculoskeletal system examples of flexibility are:
 - a. Range of motion of specific joints.
 - b. Range of motion of regions – eg spinal column.
 - c. Range of motion of muscles and muscle groups.

3. Pliability

- Supple enough to bend or stretch freely or repeatedly without breaking.
- Pliability is different to flexibility – it's more like elasticity – the ability of human tissue to stretch under load.
- As we age our skin and connective tissues generally lose elasticity. This will correlate with, but will be an extra dimension of loss of flexibility.
- In terms of the neuromusculoskeletal system examples of pliability are:
 - a. Pliability of connective tissue components.
 - b. Pliability of muscle tissue.

4. Tensegrity

- Structural stability in tensegrities depends entirely on tensional integrity or 'continuous tension / discontinuous compression'. The stability of tensegrity structures is due to the way in which their compressive and tensile load-bearing components interact.
- Many human connective tissue structures follow principles of tensegrity.
- In terms of the neuromusculoskeletal system examples of tensegrity are:
 - a. Most joint complexes are designed demonstrating tensegrity principles.
 - b. Intervertebral disc collagen arrangements.
 - c. Fascial planes which create the 3d integrity of the human body.

5. Piezoelectricity

- Electric polarization in a substance resulting from the application of mechanical stress.
- Tensegrity and Piezoelectricity are principles that go well together – one helps to explain the other.
- Many human connective tissue structures are examples of piezoelectric tissues.
- In terms of the neuromusculoskeletal system examples of piezoelectricity are:
 - a. Bony lattices which follow piezoelectric stimuli for the organization and reorganization of their configuration.
 - b. Connective tissues which generate piezoelectric currents under stress and strain, to assist with biofeedback, communication and proprioception.

6. Resilience

- Was a term used by DD Palmer which has received little attention since.
- Was used to refer to the abilities of tissues to withstand stress and strain. Perhaps similar to resilience. Also related to the idea of 'limitations of matter'.

- Probably interlinks with adaptability, flexibility and pliability but offers a component of its own in terms of the intrinsic strength of tissues to not break down under load.
- In terms of the neuromusculoskeletal system examples of renitency are:
 - a. The knife-edge between function and failure most soft and hard tissues are challenged with throughout a day and lifetime of daily activity.

5 Components of Subluxation

1. Kinesiopathology

- One component of the subluxation is biomechanical in nature. This could be manifested in a number of ways:
 - Facet joint malfunction.
 - Altered intervertebral disc dynamics.
 - Postural abnormalities.
 - Spinal misalignment.
 - Range of motion deficiencies.

2. Neuropathophysiology

- One component of the subluxation is neurological in nature. This could be manifested in a number of ways:
 - Nerve root impingement.
 - Nociceptive sensitization and altered ascending neural gateway sensitivity.
 - Referred pain possibilities.
 - Disafferentation.
 - Interference with neuropeptide and neural reward cascade pathways.

3. Myopathology

- One component of the subluxation is myofascial in nature. This could be manifested in a number of ways:
 - Hypertonicity.
 - Hypotonicity.
 - Trigger point development.
 - Sprain / strain.
 - Fibrosity.

4. Histopathology

- One component of the subluxation is biochemical in nature. This could be manifested in a number of ways:
 - Acute inflammatory response.
 - Chronic inflammatory response.
 - Neuropeptide cascade and deficiency syndrome perpetuation.
 - Interference with neurotransmitter pathways.
 - Impact on cerebrospinal fluid dynamics and nutrition.

5. Pathophysiology

- One component of the subluxation is pathological in nature. This could be manifested in a number of ways:
 - Somatopsychic effects.
 - Somato-autonomic effects.
 - Target organ changes distant to neurological compromise.
 - Chronic compensatory tissue changes in interconnected spinal structures.
 - Degenerative changes in spinal structures subjected to chronic strain.

Melzack's gate theory and subsequent neuromatrix model of the neural image

- The gate control theory explains ascending pathways of pain.
 - Explains how a modality like chiropractic can have a central input in pain management and normalization of ascending spinal gateways.
 - Explains the prioritization of painful syndromes and selective perception of dysfunction.
- The neuromatrix model better explains the descending pathways of pain.
 - Explains how higher neural function – attention, emotion, psyche, arousal – can inhibit and modify sensory experience.

The connection between the Chiropractic concept of the subluxation, and the gate control model of pain is best described by one term: Dysafferentation...

- The dysafferentation model of subluxation proposes that a vertebral subluxation causes abnormal sensory input to the central nervous system (CNS). This altered input, called dysafferentation, involves changes in the signals from mechanoreceptors and nociceptors, which can lead to compromised motor responses and other neurological dysfunctions. This model suggests that correcting the subluxation restores normal sensory processing and improves overall function.

The author proposes that the gate theory helps to explain the prioritization of normal and noxious sensory ascending signals, and that spinal subluxations have two possible pathways to interfere with these processes:

- By being a significant source of noxious afferent information.
- By interfering with the gateway processes disturbing ascending afferent information transmission and thus producing dysafferentation.

Further, it is proposed that a prioritization of the degrees of disturbance could exist, and so the concept of 'dominant neurological layers' of subluxation is suggested.

Let's try to illustrate this concept: The ascending sensory pathways and higher centres are being bombarded with immense amounts of incoming signals, some normal biofeedback, some noxious messages. Based on central processing, motor changes must be activated to maintain homeostasis and to produce normal function. We only perceive a small percentage of this process – a 'need to know' triage must occur: This is the job of the gateway systems and the neural matrix. As mentioned, subluxations play a part in this process, as sources of noxious input, and as interference to afferent pathways. And, similarly at any given time there will be variation in the degree of negative impact being made by each subluxation: This leads to the concept of the 'dominant neurological layer' as being the subluxation producing the most interference at any given time. The logical inference from this is that this 'dominant neurological layer' is the spinal level most requiring corrective input. And so, the differential diagnosis and order of corrective impulse is centred on this decision.

Further to this it is proposed that the combination of the optimum mechanotransduction potential supplied by the 3dEnergy gun, combined with a differential diagnosis of the 'dominant neurological layer' should provide an ideal therapeutic intervention. In other words, delivery of percussive forces into the spinal level of subluxation causing significant interference to the neural gateways will be an idealistic attempt for correction.

The role of dural attachments in subluxation:

There is now an extensive evidence trail describing the connective tissue attachments between the spinal column and the dura. The importance of these attachments include:

- To maintain the spinal cord in a relatively central alignment within the spinal canal
- To prevent collision and impingement between the spinal cord neural tissue and the boundaries of the spinal column

- To maintain a stable degree of tension in the CSFMU in order to protect against adverse mechanical cord tension
- To maintain a stable degree of tension in the CSFMU as a positive state of functional tensegrity and optimal piezoelectricity

Adverse mechanical spinal cord tension (AMCT) is excessive elongation or strain of the spinal meninges, a concept introduced by Alf Breig. This author proposes that spinal subluxation can have a negative impact on the preferred state of the CSFMU by creating a state of 'adverse biomechanical spinal cord interference'.

The author proposes that the management of localized spinal subluxations will have a global positive impact on the CSFMU by reducing the impact of 'adverse biomechanical spinal cord interference'.

Spinal-Dural Attachments:

Location	Name	Description
Sphenoid	Midline filum of the sellar dura	Strand-like dural extension.
Cranium		The dura mater attaches inside the skull, especially at sutures.
Occiput	Foramen Magnum	The dura is attached around the edges of the foramen magnum.
Lig nuchae or vertebral laminae of Occ / C1	Meningovertebral ligaments	
Lig nuchae or vertebral laminae of C1 / C2	Meningovertebral ligaments	
C1, C2 level	Myodural bridge	Rectus capitis posterior major.
C1, C2 level	Myodural bridge	Obliquus capitis inferior.
Posterior body of the C2 and C3		Firmly attached to the posterior surfaces of the C2 and C3 vertebral bodies.
PLL of C2 and C3	Meningovertebral ligaments	Fibrous slips.
C5	Meningovertebral ligaments	Dura to the vertebrae and denticulate ligaments on the side.
Thoracic	Hofmann's ligaments	Posterior longitudinal ligament via the fibrous bands.
Thoracic	Fibrous septum posticum	Attached to the ligamentum flavum.
Lumbar	Hofmann's ligaments	Attach the dura to the PLL and ligamentum flavum.
Sacrum		PLL via fibrous bands.
Coccyx	Filum Terminale	Terminal attachment of dura to spinal column.
Spinal Cord	Dentate Ligaments	Extension of the spinal cord's pia mater that anchors it to the dura mater, providing stability and preventing movement within the spinal canal. Usually there are 21 pairs, with the uppermost attaching near the foramen magnum and the lowermost at the T12-L1 level. These ligaments are crucial for maintaining the spinal cord's position and protecting it from injury.

Abstract Compendium:

Instrument-assisted soft tissue mobilization and percussion massage therapy in cervical disc herniation: a randomized controlled study.

J Orthop Surg Res. 2025 Aug 30;20(1):801. Burak Menek, Emre Dansuk, Sema Gorguluer.

Background: Cervical disc herniation (CDH) is a common musculoskeletal disorder characterized by chronic neck pain, impaired proprioception, kinesiophobia, and functional limitations, often requiring multimodal conservative care. Myofascial techniques, including Instrument-Assisted Soft Tissue Mobilization (IASTM) and percussion massage therapy (PMT), have emerged as supportive physiotherapy interventions. This randomized controlled trial compared the effects of IASTM and PMT on pain, disability, kinesiophobia, and proprioceptive function in individuals with CDH.

Methods: In this double-blinded RCT, 57 participants with CDH were randomly allocated to Conventional Therapy (CT), CT + PMT, or CT + IASTM (n = 19 each). Interventions were delivered three times per week for 3 weeks. PMT was applied with a percussion massage device (33-40 Hz) for 3 min to each target muscle group (trapezius, levator scapulae, cervical paravertebral) using longitudinal strokes. IASTM used stainless-steel tools on trapezius, splenius, and suboccipital muscles, with sweep and fan techniques at 30°-60°, for 9 min per session. Primary outcomes were pain (VAS) and disability (NDI); secondary outcomes included kinesiophobia (TSK) and joint position sense (JPS). Between-group differences were analyzed using ANCOVA with baseline values as covariates.

Results: All groups showed significant within-group improvements across all outcomes ($p < 0.001$). Compared to CT, both PMT and IASTM produced greater improvements in pain, kinesiophobia, and JPS ($p < 0.001$). VAS-rest reductions were -4.00 ± 0.89 ($d = 4.49$) for IASTM, -3.38 ± 1.95 ($d = 1.74$) for PMT, and -2.13 ± 1.49 ($d = 1.43$) for CT. VAS-activity decreased by -4.89 ± 1.44 ($d = 3.41$) for IASTM and -3.89 ± 1.84 ($d = 2.11$) for PMT. NDI improved by -11.47 ± 4.23 ($d = 2.71$) in IASTM, -12.11 ± 6.86 ($d = 1.76$) in PMT, and -6.63 ± 5.47 ($d = 1.21$) in CT, all exceeding the MCID threshold of 7.5 points. JPS-flexion improved by -3.80 ± 1.61 ($d = 2.36$) in IASTM, -3.67 ± 1.34 ($d = 2.73$) in PMT, and -1.09 ± 0.84 ($d = 1.29$) in CT. Similar patterns occurred for extension, right rotation, and left rotation. Overall, IASTM and PMT yielded comparable improvements, suggesting similar clinical efficacy.

Conclusions: IASTM and PMT provide added benefits over conventional therapy alone in managing CDH, especially in reducing pain and kinesiophobia and enhancing proprioception. Both can be effectively integrated into conservative rehabilitation programs targeting sensorimotor deficits in CDH.

Effect of Local Vibration Therapy on Pain, Joint Position Sense, Kinesiophobia, and Disability in Cervical Disc Herniation: A Randomized Controlled Trial.

J Clin Med. 2024 Aug 5;13(15):4566. Merve Yilmaz Menek, Emre Dansuk, Umut Islam Tayboga.

Background/Objectives: Vibration therapy approaches are an effective and safe treatment option for musculoskeletal disorders. This study examines the effects of vibration therapy using a percussion massage gun (PMG) on joint position sense, range of motion, pain, functionality, and kinesiophobia in individuals with cervical disc herniation (CDH).

Methods: This single-blind randomized controlled trial involved 44 CDH patients divided into a Vibration Group (VG) and a Conventional Group (CG). The CG underwent a standard physiotherapy treatment heat application, Transcutaneous Electrical Nerve Stimulation (TENS), and exercises for range of motion and strengthening. VG received conventional therapy augmented with vibration therapy (VT) via a PMG. Joint position sense (JPS) using the Laser Pointer Assisted Angle Repetition Test; pain intensity with the Visual Analog Scale, kinesiophobia with the Tampa Scale for Kinesiophobia, and cervical dysfunction with the Neck Disability Index were assessed.

Results: Both groups showed statistically significant improvements in pain, kinesiophobia, disability, and proprioception after treatment ($p < 0.05$). When comparing the difference values between groups, the VG was found to be more effective than the CG in the parameters of VAS activity ($p = 0.013$). The CG had more improvement in JPS neck left rotation than the VG ($p = 0.000$).

Conclusions: VT, when combined with conventional physiotherapy, is effective in improving pain, proprioception, and functionality in individuals with CDH. These findings support the inclusion of VT as a beneficial adjunct therapy. Further research with larger sample sizes and longer follow-ups is recommended to validate these results and explore the long-term effects of VT on CDH.

The Effect Of Percussive Therapy On Musculoskeletal Performance And Experiences Of Pain: A Systematic Literature Review.

Int J Sports Phys Ther. 2023 Apr 1;18(2):309-327. Lorna Sams, Ben L Langdown, Joan Simons, Jitka Vseteckova.

Background: There is a lack of specific research on the effect of percussive therapy (PT) delivered by massage guns on physiological adaptations. This systematic literature review investigates research conducted on the effects of PT interventions on performance in strength and conditioning settings, and on experiences of musculoskeletal pain.

Purpose: To determine the effect of PT delivered by massage guns on physiological adaptations: muscle strength, explosive muscle strength and flexibility, and experiences of musculoskeletal pain.

Study design: Systematic literature review.

Methods: Data sources (CINAHL, Cochrane Library, Psycinfo, PubMed, SportDISCUS and OpenGrey) were searched from January 2006 onwards for full text literature in any language involving adult populations receiving PT delivered by massage guns, directly to any muscle belly or tendon, with comparisons to an alternative treatment, placebo or no treatment. Literature with outcomes relating to acute or chronic physiological adaptations in muscle strength, explosive muscle strength, flexibility or experiences of musculoskeletal pain were included. Articles were assessed for quality using the Critical Appraisal Skills Programme and PEDro scores.

Results: Thirteen studies met the inclusion criteria. All studies had limitations in methodological quality or reporting of findings but still included contextually-rich details that contributed to the overall narrative synthesis. **A significant relationship was found between a single application of PT delivered by massage guns and an acute increase in muscle strength, explosive muscle strength and flexibility, with multiple treatments eliciting a reduction in experiences of musculoskeletal pain.**

Conclusion: **PT delivered by massage guns can help improve acute muscle strength, explosive muscle strength and flexibility, and reduce experiences of musculoskeletal pain.** These devices may provide a portable and cost-effective alternative to other forms of vibration and interventions.

The Effects of Massage Guns on Performance and Recovery: A Systematic Review.

J Funct Morphol Kinesiol. 2023 Sep 18;8(3):138. Ricardo Maia Ferreira, Rafael Silva, Pedro Vigário, Pedro Nunes Martins, Filipe Casanova, Ricardo Jorge Fernandes, António Rodrigues Sampaio.

The use of massage guns has become increasingly popular in recent years. Although their use is more and more common, both in a clinical and sports context, there is still little information to guide the practitioners. This systematic review aimed to determine the effects of massage guns in healthy and unhealthy populations as pre- and post-activity or part of a treatment. Data sources used were PubMed, PEDro, Scopus, SPORTDiscus, Web of Science and Google Scholar, and the study eligibility criteria were based on "healthy and unhealthy individuals", "massage guns", "pre-activity, post-activity or part of a treatment" and "randomized and non-randomized studies" (P.I.C.O.S.). Initially, 281 records were screened, but only 11 could be included. Ten had a moderate risk of bias and one a high risk of bias. Massage guns could be effective in improving iliopsoas, hamstrings, triceps suralis and the posterior chain muscles' flexibility. In strength, balance, acceleration, agility and explosive activities, it either did not have improvements or it even showed a decrease in performance. In the recovery-related outcomes, massage guns were shown to be cost-effective instruments for stiffness reduction, range of motion and strength improvements after a fatigue protocol. No differences were found in contraction time, rating of perceived exertion or lactate concentration. **Massage guns can help to improve short-term range of motion, flexibility and recovery-related outcomes,** but their use in strength, balance, acceleration, agility and explosive activities is not recommended.

Investigating the effects of percussion massage therapy on pain, functionality, muscle diameter, and proprioception in individuals with ACL reconstruction: a randomized controlled trial.

PLoS One. 2025 Mar 26;20(3): e0319731. Beyza Nur Erayata, Burak Menek.

Background: **Percussion massage therapy (PMT) integrates traditional massage with vibration therapy.** This study examined the effects of adding PMT to a structured exercise program for individuals who underwent surgery after an anterior cruciate ligament (ACL) injury.

Methods: A total of 24 individuals aged 18-40 were included in the study. Participants were divided into the PMT and structured exercise groups (SEG). The SEG group received a progressive neuromuscular exercise program, and the PMT group received the same structured exercise program and PMT. Range of motion (ROM) was assessed using the Goniometer Pro smartphone application, joint position sense (JPS) was measured goniometer, pain intensity was evaluated with the Visual Analog Scale (VAS), functionality was assessed using the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), balance was measured with the Berg Balance Scale, quality of life was evaluated using the Short Form-36 (SF-36), and muscle diameter was measured via ultrasonography.

Results: Significant improvements were observed in all parameters in both groups post-treatment ($p < 0.05$). **The PMT group showed superior results** compared to the SEG group in ROM, JPS (60°), pain, functionality, balance, and quality of life (particularly in the general health perception sub-parameter of SF-36) ($p < 0.05$).

Conclusions: The findings of this study suggest that **incorporating PMT, a novel approach in the literature, into the rehabilitation program following ACL reconstruction could be effective. PMT could be an alternative treatment method that can be used in conjunction with exercise programs in ACL rehabilitation.**

The effect of percussion massage therapy on the recovery of delayed onset muscle soreness in physically active young men-a randomized controlled trial

Front Public Health. 2025 Mar 26; 13: 1561970. Haiwei Li, Liang Luo, Jing Zhang, Peipei Cheng, Qiang Wu, Xinping Wen.

Background: Delayed onset muscle soreness (DOMS) is a common condition among physically active individuals, often resulting in reduced performance and discomfort. Although percussive massage treatment (PMT) is widely used as a recovery tool, there is limited evidence supporting its efficacy compared to traditional methods such as static stretching.

Objective: To investigate the effect of PMT on recovery from DOMS in physically active young men.

Methods: Thirty physically active male college students were randomized into three groups: static stretching (SS) group, a short-duration PMT (S-PMT) group, and a long-duration PMT (L-PMT) group. All participants performed squats to induce DOMS, followed by interventions of static stretching, 25 min of PMT, or 40 min of PMT, respectively. Measurements included the visual analog scale (VAS) pain score, knee joint range of motion (ROM), countermovement jump (CMJ), and integrated electromyography (iEMG). These were measured at baseline (P0), post-DOMS protocol (P1), post PMT (P2), 24 h post-intervention (P3), and 48 h post-intervention (P4). Data were analyzed using repeated-measures ANOVA or nonparametric tests, with multiple comparisons conducted at a significance level of $p < 0.05$.

Results: Compared with the SS and S-PMT group, the L-PMT group at P4 demonstrated significantly greater jump height (SS group: $p < 0.001$, $d = 8.691$; S-PMT group: $p = 0.006$, $d = 4.37$), peak ground reaction force (SS group: $p < 0.001$, $d = 19.174$; S-PMT group: $p < 0.001$, $d = 14.334$), and propulsion impulse (SS group: $p < 0.001$, $d = 8.302$; S-PMT group: $p = 0.003$, $d = 4.517$) during the CMJ propulsion phase. Additionally, the normalized iEMGs of the three muscles in the L-PMT group were significantly lower than those in the S-PMT (VM: $p < 0.001$, $d = -5.692$; RF: $p < 0.001$, $d = -8.222$; VL: $p < 0.001$, $d = -10$) and SS groups at P4 (VM: $p < 0.001$, $d = -12$; RF: $p < 0.001$, $d = -11.384$; VL: $p < 0.001$, $d = -15$). At P4, the L-PMT group exhibited significantly lower VAS scores than the SS group ($p = 0.003$, $d = -1.53$), as well as significantly greater knee joint ROM compared to the SS group ($p = 0.012$, $d = 4.77$).

Conclusion: PMT was more effective than static stretching for DOMS recovery. Furthermore, two 40-min PMT sessions provided greater benefits than two 25-min sessions for treating DOMS. These findings suggest that PMT can be a valuable tool for physically active individuals seeking to enhance recovery and maintain performance.

Percussion Massage Therapy Reduced EMG Activity During Standing Heel Raise.

J Musculoskelet Neuronal Interact. 2025 Sep 1;25(3):307-315. Mikulas Hank, Lukas Michal, Dai Sugimoto, Ferdia Fallon Verbruggen, Pavol Pivovarnicek, Petr Miratsky, Frantisek Zahalka, Tomas Maly.

Objectives: This study examined the acute impact of percussion massage therapy (PMT) on calf muscle activation during heel raises in individuals with and without chronic ankle instability (CAI).

Methods: Thirty-nine university students, 20 with CAI and 19 controls, were randomized to 30 seconds of PMT or no intervention (NOPMT). Surface EMG measured medial gastrocnemius activity during heel raise before and after.

Results: Pre-intervention, CAI limbs displayed significantly lower peak muscle activation than limbs without CAI (26%, $p = 0.012$). Post-intervention, both PMT groups showed significant reductions in peak EMG (CAI: 10%, controls: 12%, $p < 0.05$), while NOPMT groups remained unchanged.

Conclusion: These results indicate CAI is associated with reduced calf muscle activation, and PMT further decreases it. However, PMT's activation-reducing effect may be counterproductive when increased muscle activation is desired, necessitating further research on PMT's interaction with activation exercises. Further research is needed to explore the long-term effects and optimal timing of PMT in rehabilitation and athletic settings.

A Comparison of the Acute Effects of Percussion Massage Therapy and Static Stretching on Hamstring Elasticity.

Ethiop J Health Sci. 2023 Jul;33(4):695-702. Rumeysa Ateş, Pinar Yaşar, Ferdi Başkurt, Zeliha Başkurt, Sabriye Ercan.

Background: The effect of percussion massage on hamstring flexibility is unknown. This study aimed to investigate the acute effects of percussion massage on hamstring flexibility and to compare its effectiveness with static stretching.

Methods: Fifty-four healthy individuals aged 18-25 years with at least 15 degrees of active knee extension were included in the study. The study was conducted between February and May 2022. The participants were randomly divided into 3 groups in this cross-randomization study as percussion massage ($n=18$), static stretching ($n=18$), and control ($n=18$). The Active Knee Extension test and the Sit and Reach test were used as evaluation parameters, and assessments were performed pre-intervention and 30 min post-intervention (acute).

Results: In both percussion and stretching intervention groups, the range of motion (ROM) gain in the Active Knee Extension test was statistically significant ($p < 0.05$) compared to the control group. Active knee extension angle gain was similar between percussion and stretching interventions ($p > 0.05$). It was found that hamstring flexibility improved significantly in both percussion massage and static stretching groups ($p < 0.05$). However, considering the last measurement and flexibility gain values, it was found that percussion massage and static stretching had similar acute effects on hamstring muscle flexibility ($p > 0.05$).

Conclusion: Percussion massage had an acute positive effect on hamstring flexibility and ROM, and it was as effective as static stretching. Therefore, percussion massage devices are recommended as part of pre-exercise in a structured warm-up for increase in joint range of motion and flexibility.

Consumer Perceptions of Home-Based Percussive Massage Therapy for Musculoskeletal Concerns: Inductive Thematic Qualitative Analysis

JMIR Rehabil Assist Technol. 2024 Feb 5;11:e52328. Saloni Butala, Pearl Valentine Galido, Benjamin K P Woo.

Background: Musculoskeletal pain is a prevalent concern among diverse populations, from the average individual to the elite athlete. Handheld percussive massage therapy devices like massage guns have gained much popularity in both medical and athletic settings. Its application has been prominently recognized in injury prevention and

rehabilitation. The expansion of the market to provide handheld percussive therapy devices with varying features and price points has encouraged professional and novice use. While percussive therapy holds similarities to more studied therapeutic modalities, like vibration therapy and soft tissue mobilization, there is limited evidence-based information on the indications and contraindications.

Objective: This study aims to use a qualitative analysis of consumer perceptions to understand the perceived therapeutic potential of percussive massage therapy as a home-based intervention for musculoskeletal concerns of everyday users and elite athletes. Additionally, we aim to gain insight on valuable characteristics supporting its therapeutic potential as well as pertinent limitations.

Methods: The TOLOCO massage gun (TOLOCO) was identified as the best-selling percussive massage therapy device on Amazon. We performed an inductive thematic qualitative analysis on the top 100 positive comments and the top 100 critical comments of the device between June 2020 and April 2023 to determine 4 relevant themes.

Results: The 4 themes identified upon qualitative analysis were pain management, versatility, accessibility, and safety and user education. Consumer reviews indicated use for this percussive therapy device in adolescents, adults, and older people across a spectrum of activity levels. Consumers reported the therapeutic potential of percussive massage therapy in managing wide-ranging musculoskeletal concerns like acute pain, chronic pain, nonsurgical injury rehabilitation, postsurgical injury rehabilitation, and injury prevention. Consumers highlighted the versatility of the device to address person-specific needs as a key feature in supporting its perceived therapeutic benefits. Additionally, consumers frequently commented on the affordability and availability of this device to increase accessibility to home-based care. Some critical reviews emphasized a concern for the quality of the device itself. However, this concern did not translate to the overall modality of percussive massage therapy. Of note, despite strong approval for its therapeutic potential, consumer reviews lacked evidence-based insights on appropriate usage.

Conclusions: Home-based percussive massage therapy holds value with its perceived efficacy in pain management for acute and chronic conditions, as well as in injury prevention and rehabilitation. As a low-cost and readily available device for everyday users and high-performing athletes, percussive massage therapy works toward establishing increased health care accessibility and optimizing health care usage. This home-based intervention can serve to reduce the significant personal and economic burden of prevalent musculoskeletal concerns. However, the limited scientific research on percussive massage therapy raises concerns about the lack of evidence-based care and indicates the need for future studies.

The Immediate Effect of Percussive Massage Therapy on Iliotibial Band Tightness in Field Athletes.

Cureus. 2025 Jan 12;17(1):e77348. Pallavi R Bhakaney, Sandhya N Towar, Tushar J Palekar, Ishan Shevate, Mrudula Sangaonkar.

Background and objective: Iliotibial band tightness (ITBT) is a common knee injury that usually presents with pain and tenderness on palpation of the lateral aspect of the knee, superior to the joint line and inferior to the lateral femoral epicondyle. Athletes with ITBT typically complain of a sharp or burning pain roughly 2 cm superior to the lateral joint line. The pain may radiate proximally or distally, and in less severe cases, the pain may quickly subside upon cessation of activities. New approaches such as percussive massage therapy are used to relax the muscle tissue, reduce discomfort, and improve blood flow. It involves the use of handheld percussion devices to apply rapid vibrations and percussions to the skin and underlying soft tissue. This study aimed to examine the immediate effectiveness of percussive massage therapy on the responsiveness of pain and range of motion (ROM) in field athletes.

Methodology: Fifty athletes between the ages of 20 and 35 years were recruited for the study based on inclusion and exclusion criteria. The immediate effectiveness of percussive massage therapy (Caresmith Massage Gun, Caresmith, Mumbai, India) was assessed based on the pre-treatment and post-treatment pain levels measured on the Numerical Pain Rating Scale (NPRS) score and ROM of hip abduction and knee flexion.

Results: The results indicated a significant decrease in post-treatment pain, with the mean NPRS score decreasing from 5.18 to 2.60 immediately following the session. While the majority of participants experienced a decrease in NPRS scores, a few reported no change. The t-test for the right hip abduction ROM demonstrated a significant group effect ($p < 0.001$). The t-test for the right knee flexion ROM also demonstrated a significant group effect ($p < 0.001$).

Conclusions: The current study indicates that the majority of the field athletes showed a positive response to percussion massage therapy in terms of pain and ROM.

Acute effects of handheld percussive massage therapy on various posterior shoulder soft tissue areas in healthy young males

J Sports Med Phys Fitness. 2025 Jun;65(6):778-786. Takaki Imai, Takashi Nagamatsu, Yushin Yoshizato, Kodai Miyara, Megumi Sumizono, Masatoshi Nakamura.

Background: Interventions using vibration stimulation can increase the range of motion (ROM) without compromising muscle strength. Handheld percussive massage directly stimulates the focal area. Therefore, its effectiveness may be affected depending on the areas of stimulation. Thus, this study aimed to compare the effects of handheld percussive massage to different stimulation areas on shoulder internal rotation ROM and shoulder external rotation muscle strength and torque.

Methods: This crossover study included 15 healthy male volunteers (20.6 ± 1.5 years). A 5-min percussive massage was applied to three posterior shoulder areas: the muscle belly, proximal muscle-tendon junction, and distal muscle-tendon junction. Internal rotation ROM (vertebral level and abduction position) and external rotation muscle strength (isometric and concentric) were measured before and immediately after the intervention and compared.

Results: Internal rotation ROM (vertebral level and abduction position) showed a time effect ($P < 0.05$). No interaction or between-condition effects were observed. Post hoc testing showed a change in internal rotation ROM (vertebral level and abduction position) after intervention at the three stimulation areas ($P < 0.05$). Muscular strength did not show any interaction, time, or between-condition effects.

Conclusions: Handheld percussive massage therapy to various posterior shoulder soft tissue areas increased the internal rotation ROM without decreasing the external rotation maximum voluntary contraction torque.

Acute Effects of Handheld Vibration Massage on Posterior Shoulder Soft Tissues

Int J Sports Phys Ther. 2024 Aug 2;19(8):1003-1011. Takaki Imai, Takashi Nagamatsu, Yushin Yoshizato, Kodai Miyara, Megumi Sumizono, Masatoshi Nakamura.

Background: Interventions using vibration stimulation have been recognized for their potential for increasing range of motion (ROM) without compromising muscle strength. Handheld vibration massagers can efficiently deliver vibration therapy to the shoulder joint and may be a potential treatment.

Purpose: To evaluate the effects of vibration massage using a handheld device on the soft tissues of the posterior shoulder joint, particularly on internal rotation (IR) passive ROM and external rotation (ER) muscle strength.

Study design: Crossover study design.

Methods: A crossover study with a 5-min vibration massage and passive control condition was conducted in healthy male volunteers (mean age 20.5 ± 1.7 years). Vibration massage was applied to the posterior shoulder soft tissues of the dominant arm, with no intervention under control conditions. IR-ROM (vertebral level and in abduction) and strength of the external rotators (isometric and isokinetic) were measured before and immediately after the intervention. Vertebral levels were calculated as a ratio of lengths (ratio decreases with increased mobility). IR-ROM in abduction, the angle was measured. Statistical analysis was performed with two-way repeated measures ANOVA and paired t-test (Bonferroni correction).

Results: Vibration application decreased (improved) vertebral level IR ROM by -4.1% ($p < 0.01$, $d = 0.445$) and increased abduction position IR ROM by 11.4° ($p < 0.01$, $d = 0.694$). These changes exceeded the 95% confidence interval for the minimum detectable change. By contrast, the control condition produced no changes. IR-ROM (vertebral level and abduction) immediately after the intervention showed significant differences between the control and vibration conditions ($p = 0.036$, $d = 0.273$; $p = 0.048$, $d = 0.483$, respectively). Muscle strength did not show any interaction, time, or between-condition effects.

Conclusions: A massage using a handheld vibration massager applied to the posterior shoulder soft tissues increased IR-ROM without negatively affecting muscle strength, suggesting its potential use as a means of warming up.

The Acute Effects of a Percussive Massage Treatment with a Hypervolt Device on Plantar Flexor Muscles' Range of Motion and Performance

J Sports Sci Med. 2020 Nov 19;19(4):690-694. Andreas Konrad, Christoph Glashüttner, Marina Maren Reiner, Daniel Bernsteiner, Markus Tilp.

Handheld percussive massage treatment has gained popularity in recent years, for both therapeutic use and in sports practice. It is used with the goals of increasing flexibility and performance, but also to accelerate recovery. However, until now, there has been no scientific evidence, which proves such effects. Therefore, the purpose of this study was to investigate the effects of a 5-min percussion treatment of the calf muscles on range of motion (ROM) and maximum voluntary contraction (MVC) torque of the plantar flexor muscles. Sixteen healthy male volunteers (mean $\pm$ SD; 27.2 ± 4.2 years, 1.79 ± 0.05 m, 79.4 ± 9.1 kg) were tested on two separate days with either a 5-min massage treatment of the calf muscles with a Hypervolt device or the control condition (sitting only). Before and after the treatments, dorsiflexion ROM and MVC torque of the plantar flexor muscles were measured with a dynamometer. Maximum dorsiflexion ROM increased with a large magnitude following the massage treatment by 5.4° ($+18.4\%$; $p = 0.002$, $d = 1.36$), while there was no change in the control group. Moreover, MVC torque did not change following both the massage treatment and the control treatment. Similar to a conventional massage by a therapist, ROM can be increased by a handheld percussive massage treatment without having an effect on muscle strength.

The Acute Effect of Percussive Massage Intervention with and without Heat Application on Plantar Flexor Muscles' Passive and Active Properties

J Sports Sci Med. 2024 Mar 1;23(1):73-78. Masatoshi Nakamura, Hironori Uchida, Yuta Murakami, Kazuki Kasahara, Takaki Imai, Andreas Konrad.

Recently, percussive massage (PM) intervention using a handheld percussive massage device, namely a massage gun, has been used as an easy way to perform vibration functions. Additionally, a product has been developed that allows PM intervention and heat application to be performed simultaneously. Thus, this study aimed to compare the acute effects of PM intervention with and without heat application on dorsiflexion (DF) range of motion (ROM), passive

stiffness, and muscle strength in the gastrocnemius muscle. Fifteen healthy young men (20.9 ± 0.2 years) participated in this study. We measured the DF ROM, passive torque at DF ROM (an indicator of stretch tolerance), passive stiffness, and maximum voluntary isometric contraction (MVIC) torque of the plantar flexor muscles before and immediately after 120 seconds PM intervention with and without heat application. **The results showed that PM intervention with and without heat application significantly increased DF ROM and passive torque at DF ROM and decreased passive stiffness, not MVIC torque. These results suggest that PM intervention increased ROM and decreased passive stiffness regardless of the presence or absence of the heat application.**

Acute Effects of Percussive Massage Treatment on Drop Jump Performance and Achilles Tendon Stiffness.

Int J Environ Res Public Health. 2022 Nov 17;19(22):15187. Patryk Szymczyk, Kamil Węgrzynowicz, Robert Trybulski, Michał Spieszny, Paulina Ewertowska, Michał Wilk, Michał Krzysztofik.

This study aimed to investigate the impact of Achilles tendon (AT) mechanical percussion massage (PM) on the passive stiffness of that tendon and subsequent drop jump kinematics. Eleven physically active participants performed two conditions in random order: (i) 60 s of PM applied to each AT (EXP) and (ii) no PM (CTRL). Measurements were performed 5 min before, immediately after, and 5 min following the completion of the PM. In the CTRL, measurements were performed at the same time point but no massage was applied. The two-way ANOVA indicated that there was no statistically significant interaction effect on contact time ($p = 0.786$), reactive strength index ($p = 0.914$), and relative peak power ($p = 0.896$). However, a statistically significant interaction on peak velocity ($p = 0.046$) and jump height ($p = 0.03$) was found. Despite that, there was no significant post-hoc comparisons for jump height, it slightly decreased 5 min post-PM ($p = 0.136$; ES = -0.25; $\Delta = -3.1\%$) compared with the CTRL condition ($p = 1.00$; ES = 0.11; $\Delta = +1.5\%$). Friedman's test did not show significant differences in dominant ($p = 0.073$) and non-dominant limb ($p = 0.091$) AT stiffness. Although not significant, numerically, the dominant limb AT ($p = 0.126$; ES = -0.64; $\Delta = -7.8\%$) had a larger reduction in stiffness immediately post-PM compared with the non-dominant limb ($p = 0.294$; ES = -0.26; $\Delta = -3.6\%$). **The results of this study indicated the temporary effect of PM on the reduction in tissue stiffness.** Moreover, these findings show that a mechanical PM might slightly hinder subsequent explosive athletic performance.

Functional and Structural Long-Term Effects of Repetitive Instrument-Assisted Manual Therapy (IAMT) of the Lumbar Back on the Dorsal Myofascial Chain Among Female Soccer Players: A Randomized, Placebo-Controlled Pilot Trial.

Cureus. 2024 Sep 13;16(9):e69337. Patrick Weber, Werner Klingler, Robert Schleip, Nadine Weber, Christine Joisten.

Introduction: Instrument-assisted manual therapy (IAMT) is suitable for optimizing movement prerequisites, such as range of motion, flexibility, microcirculation, and pain inhibition along myofascial chains, potentially leading to a reduction in hamstring injuries. To date, however, IAMT's modes of action remain largely unclear. This study aimed to examine the functional and structural effects of repetitive IAMT after 2.5 and five weeks.

Methods: Sixteen healthy female soccer players (age: $21.4 (\pm 5.1)$ years) were randomly grouped into an intervention group and a placebo control group. The intervention group received nine IAMT sessions twice weekly at the right lumbar region. The placebo group received a single pressureless "therapy" at baseline. In addition to structural ultrasound analyses (absolute motion and shear motion), functional mobility tests (passive straight leg raise (PSLR) test and lumbar and thoracic double inclinometry) were performed $4.0 (\pm 2.0)$ days after the fourth IAMT and $3.4 (\pm 1.1)$ days after the ninth IAMT in both groups.

Results: Hamstring flexibility in the PSLR test improved significantly after the ninth IAMT compared with the placebo group ($p < 0.05$, effect size: 0.913). No systematic differences were seen at the structural level.

Conclusion: **Repetitive IAMT can improve hamstring flexibility.** Further studies in larger groups and diverse collectives are necessary to additionally test the postulated preventive effect also on hamstring injuries. Whether ultrasound is the right method for detecting structural changes in this context needs to be verified in the future.

Effects of Percussive Massage Treatments on Symptoms Associated with Eccentric Exercise-Induced Muscle Damage.

J Sports Sci Med. 2024 Mar 1;23(1):126-135. Trevor D Roberts, Pablo B Costa, Scott K Lynn, Jared W Coburn.

Percussive massage (PM) is an emerging recovery treatment despite the lack of research on its effects post-eccentric exercise (post-EE). This study investigated the effects of PM treatments (immediately, 24, 48, and 72 h post-EE) on the maximal isometric torque (MIT), range of motion (ROM), and an 11-point numerical rating scale (NRS) of soreness of the nondominant arm's biceps brachii from 24-72 h post-EE. Seventeen untrained, college-aged subjects performed 60 eccentric elbow flexion actions with their nondominant arms. Nine received 1 minute of PM, versus eight who rested quietly (control [CON]). In order, NRS, ROM, and MIT (relative to body mass) were collected pre-eccentric exercise (pre-EE) and after treatment (AT) at 24, 48, and 72 h post-EE. NRS was also collected before treatment (BT). Electromyographic (EMG) and mechanomyographic (MMG) amplitudes were collected during the MIT and normalized to pre-EE. There were no interactions for MIT, EMG, or MMG, but there were interactions for ROM and NRS. For ROM, the PM group had higher values than the CON 24-72 h by $\sim 6-8^\circ$, a faster return to pre-EE (PM: 48 h, CON: 72 h), and exceeded their pre-EE at 72 h by $\sim 4^\circ$. The groups' NRS values did not differ BT 24-72 h; however, the PM group lowered their NRS from BT to AT within every visit by ~ 1 point per visit, which resulted in them having lower values than the CON from 24-72 h by $\sim 2-3$ points. Additionally, the PM group returned their NRS to pre-EE faster than the CON (PM: BT 72 h, CON: never). In conclusion, **PM treatments may improve ROM without affecting isometric strength or muscle activation 24-72 h post-EE. Although the PM treatments did not enhance the recovery from**

delayed onset muscle soreness until 72 h, they consistently provided immediate, temporary relief when used 24-72 h post-EE.

Physiological Effects of Local Theragun™ Application: An Observational Study in Healthy Female Participants.

Int J Sports Phys Ther. 2025 Jul 2;20(7):1018-1028. Ron Clijssen, Livia Freitag, Erich Hohenauer, Giannina Bianchi.

Background: While the clinical effects of localized percussive therapy (PT) are well-documented, studies investigating the underlying physiological mechanisms remain scarce.

Purpose: The aim of this study was to investigate the changes and time course of local skin temperature (T_{skin}), deep tissue perfusion (erythrocyte flow velocity [speed] and deep tissue blood flow [flux]), and muscle oxygenation (SmO₂) after a standardized 4-minute treatment with a Theragun™ of the vastus medialis muscle of healthy women.

Study design: Descriptive Laboratory Study.

Methods: T_{skin}, speed, flux and SmO₂ were measured in the treated area in 26 healthy female participants at baseline and following a 4-minute Theragun™ application, with recordings taken at 5-minute intervals for up to 50 minutes post-application. Additionally, T_{skin} was also measured on the control leg. A repeated measures ANOVA was performed to assess temporal changes and differences between the treated and control conditions.

Results: Following the Theragun™ treatment, significant increases were observed in the treated area at all time points for T_{skin} ($p < 0.001$), speed ($p < 0.001$), flux ($p < 0.001$), and SmO₂ ($p < 0.05$) compared to baseline. T_{skin} (mean change of 3.76 °C) and SmO₂ (mean change of 5.78%) reached their highest values at five minutes post-treatment (t₅), whereas speed (mean change of 23.79 arbitrary units [AU]) and flux (mean change of 115.66 AU) peaked immediately (t₀) after the application. T_{skin} on the control leg also differed significantly across all time intervals compared to baseline ($p < 0.05$), peaking at t₃₀ (mean change 0.64°C).

Conclusion: A 4-minute localized Theragun™ application enhances physiological responses in cutaneous, subcutaneous, and muscle tissues. It increases skin temperature and improves deep tissue blood flow, red blood cell movement, and muscle oxygenation. These findings highlight the impact of Theragun™ on deep tissue layers, offering valuable insights into the physiological mechanisms of PT. The results support the potential for its use in optimising athletic performance and recovery through enhanced blood flow and muscle oxygenation.

The Acute Effects of Cold Water Immersion and Percussive Massage Therapy on Neuromuscular Properties and Muscle Soreness after Exercise in Young Male Soccer Players.

Sports (Basel). 2024 Jun 15;12(6):167. Alex Buoite Stella, Angelo Michele Dragonetti, Simone Fontanot, Raffaele Sabot, Miriam Martini, Alessandra Galmonte, Gianluca Canton, Manuela Deodato, Luigi Murena.

Cold water immersion (CWI) and percussive massage therapy (PMT) are commonly used recovery techniques in team sports. In particular, despite its wide use, PMT has been scarcely investigated in the literature, especially regarding neuromuscular measures and in comparison with other techniques. This study aimed to evaluate and compare the acute and short-term effects (24 h) of CWI and PMT on muscle strength, contractile properties, and soreness after exercise. A randomized crossover study was performed on sixteen male soccer players (22 years, 20-27) who participated in three experimental sessions involving a fatiguing protocol consisting of a Yo-Yo Intermittent Endurance Test followed by 3 × 10 squat jumps and a wall sit for 30 s, and 12 min of recovery including CWI (10 °C water), bilateral PMT on the anterior and posterior thigh, or passive resting. Outcomes were assessed immediately after the exercise protocol, after the recovery intervention, and at 24 h. Isometric knee extension (IKE) and flexion (IKF) and tensiomyography (TMG) were assessed. Muscle soreness and fatigue were scored from 0 to 10. PMT increased strength after the treatment ($p = 0.004$) and at 24 h ($p = 0.007$), whereas no significant differences were found for the other two recovery modalities. At post-recovery, compared to CON, CWI resulted in a longer TMG contraction time ($p = 0.027$). No significant differences were found at 24 h. Finally, PMT and CWI enhanced muscle soreness recovery compared to passive rest ($F_{4,60} = 3.095$, $p = 0.022$, $\eta^2 = 0.171$). Preliminary results from this study suggest that PMT might improve isometric strength after strenuous exercise, and both PMT and CWI reduce muscle soreness perception, while the effects on TMG parameters remain controversial.

A comparison of dynamic warm-up and "warm-up" using self-massage tools on subsequent sit-and-reach displacement.

PLoS One. 2024 Aug 22;19(8):e0307073. Michele Aquino, Frederick DiMenna, John Petrizzo, George Yusuff, Robert M Otto, John Wygand.

Objectives: A dynamic warm-up (DWU) comprising exercise involving rhythmic muscle actions results in an acute increase in range of motion; however, recent findings suggest that a passive one using self-massage techniques might elicit a similar effect. This study's purpose was to compare the acute effect of leg cycling DWU on sit-and-reach score to the effect of a preparatory regimen of foam rolling (FR) or percussive massage (PM).

Design: Single-blind, randomized, repeated-measures crossover study.

Methods: Thirty-two asymptomatic, physically-active participants (male; $n = 17$) aged 20.9 ± 1.5 years performed sit-and-reach tests before, immediately following and 10-, 20- and 30-minutes following eight minutes of each of the "warm-ups." Analyses of variance at each time point across conditions and for the percent change elicited by each intervention were conducted to determine significant differences ($p < 0.05$).

Results: Repeated-measures ANOVA revealed a significant difference between mean percent difference of sit-and-reach score for FR ($8.8 \pm 0.5\%$) compared to DWU and PM ($p = 0.046$ and 0.048 , respectively) while DWU ($6.3 \pm 0.8\%$) and PM ($6.8 \pm 0.5\%$) did not differ ($p = 0.717$). There were no differences between scores across interventions at any of the four time points.

Conclusions: A bout of FR or PM resulted in an acute increase in a sit-and-reach score during a test performed immediately post and at 10-, 20- and 30-minutes post that was similar in magnitude to that which was present following leg cycling. These passive "warm-ups" are appropriate alternate strategies that can be employed to improve performance on a sit-and-reach test.

Acute Effects of Local High-Frequency Percussive Massage on Deep Fascial and Muscular Stiffness and Joint Range of Motion in Young Adult Men.

J Sport Rehabil. 2024 Mar 20;33(4):252-258. Zijian Liu, Yicheng Zhong, Toshihiro Maemichi, Qianhui Zhou, Takumi Okunuki, Yanshu Li, Wakamiya Kazuki, Tsukasa Kumai.

Background: Local high-frequency percussive (HFP) massage has recently found widespread application in physical therapy. Although HFP massage reportedly improves range of motion (ROM), the mechanism underlying its action has not yet been proven. This study aimed to clarify whether a 5-minute percussive massage regimen affects muscular or connective tissues, such as the deep fascia and deep intermuscular fascia and the change in joint ROM.

Method: The study sample was calculated using G*Power analysis program, and this study enrolled 15 healthy men who underwent 5-minute HFP massage to the medial gastrocnemius muscle. Shear-wave elastography was used to measure tissue stiffness in the deep fascia, muscle, and deep intermuscular fascia through shear-wave velocity as well as the ROM of the volunteers' ankle joint dorsiflexion before and after the HFP massage. A value of $P < .05$ was used to declare statistical significance, and post hoc was used to calculate the effect size using G*Power.

Results: Shear-wave velocity revealed a significant change in the deep fascia ($P = .003$; shear-wave velocity: -0.7 m/s) and significant increase in ROM of ankle dorsiflexion ($P = .002$; increase in ROM: 3.0°) after 5 minutes of HFP massage. However, the muscle and deep intermuscular fascia did not exhibit any significant changes.

Conclusions: HFP massage for 5 minutes modified the stiffness of the deep fascia and concurrently improved the ankle joint-dorsiflexion ROM. This method can be used as an intervention to decrease stiffness of the deep fascia and increase the ROM efficiently.

Foam Rolling or Percussive Massage for Muscle Recovery: Insights into Delayed-Onset Muscle Soreness (DOMS).

J Funct Morphol Kinesiol. 2025 Jun 29;10(3):249. Sebastian Szajkowski, Jarosław Pasek, Grzegorz Cieślak.

Background: Pain manifestations as well as increased muscle tone and stiffness noted in the course of delayed-onset muscle soreness (DOMS) are reflected in altered values of the biomechanical and visco-elastic parameters of muscles. This study aimed to compare the effects of soft tissue mobilization with foam rolling and percussive massage on symptoms of DOMS induced by a standardized muscle fatigue protocol.

Methods: Healthy volunteers ($n = 60$) were divided into three groups: FR group-foam rolling ($n = 20$), PM group-percussive massage ($n = 20$) and CON group-control/passive rest ($n = 20$). The fatigue protocol for the gastrocnemius muscle was carried out for development of DOMS in subsequent days. Therapeutic procedures were applied to participants for 3 consecutive days. The results of therapy were assessed by means of myotonometry, performed five times (before, three times during the treatment procedure, and after the end of the procedure).

Results: Foam rolling significantly reduced the onset and duration of increased muscle tone ($p = 0.006$) and stiffness ($p < 0.001$), unlike percussive massage. The control group exhibited higher tone and stiffness after 48 h, at the peak of DOMS-related pain symptoms. Only foam rolling improved elasticity (decrement, $p < 0.001$), while visco-elastic properties (relaxation, creep) varied inversely with tone and stiffness. Foam rolling led to significantly lower stiffness (day 2) and reduced decrement and relaxation (day 4) compared to the control. Neither therapy was more effective than passive rest for pain relief during the observation period.

Conclusions: Foam rolling and percussive massage accelerate recovery of muscle tone, stiffness, and elasticity after DOMS as compared to passive rest but offer no added benefit for pain relief.

Comparison of the impacts of percussion massage therapy, dynamic stretching, and kinesiology taping techniques on functional performance, muscular strength, and proprioception in the shoulder

Work. 2025 May;81(1):2389-2398. Burak Menek, Umut Islam Tayboga.

Background: Percussion massage therapy (PMT) integrates traditional massage with vibration therapy.

Objective: This study compared the effects of percussion massage therapy (PMT), kinesiology tape (KT), and dynamic stretching (DS) on shoulder strength, proprioception, and functionality.

Methods: The KT group had kinesiology tape applied to the deltoid muscles. The DS group performed dynamic stretching in flexion and abduction. The PMT group received percussion massage on the deltoid muscles. Assessments included the Beure system for joint position sense (JPS), the Timed Functional Arm and Shoulder Test (TFAST), and a hand-held dynamometer for muscle strength.

Results: Significant improvements were observed in almost all JPS parameters for all groups ($p < 0.05$). Total TFAST scores improved in all groups. Muscle strength significantly improved in the DS group ($p < 0.05$), while PMT and KT groups showed no significant change ($p > 0.05$). Statistically significant differences were found between the groups ($p < 0.05$). JPS 30°, 60°, and 90° flexion parameters had effect sizes of 0.51, 0.64, and 0.49, respectively; JPS 30°, 60°, and 90° abduction parameters had effect sizes of 0.38, 0.46, and 0.45, respectively. The effect size for Total TFAST was 0.55, flexion muscle strength 0.59, and abduction muscle strength 0.68. DS was more effective for muscle strength, DS and PMT for functionality, and KT and PMT for proprioception ($p < 0.017$).

Conclusions: PMT and KT were more effective for proprioception, PMT and DS were more effective for functionality, and DS was most efficient in enhancing muscle strength.

Effect of Localized Vibration Massage on Popliteal Blood Flow.

J Clin Med. 2023 Mar 4;12(5):2047. Devin Needs, Jonathan Blotter, Madison Cowan, Gilbert Fellingham, A Wayne Johnson, Jeffrey Brent Feland.

There is a broad scope of literature investigating whole-body vibration (WBV) effects on blood flow (BF). However, it is unclear how therapeutic localized vibrations alter BF. Low-frequency massage guns are advertised to enhance muscle recovery, which may be through BF changes; however, studies using these devices are lacking. Thus, the purpose of this study was to determine if popliteal artery BF increases from localized vibration to the calf. Twenty-six healthy, recreationally active university students (fourteen males, twelve females, mean age 22.3 years) participated. Each subject received eight therapeutic conditions randomized on different days with ultrasound blood flow measurements. The eight conditions combined either control, 30 Hz, 38 Hz, or 47 Hz for a duration of 5 or 10min. BF measurements of mean blood velocity, arterial diameter, volume flow, and heart rate were measured. Using a cell means mixed model, we found that both control conditions resulted in decreased BF and that both 38 Hz and 47 Hz resulted in significant increases in volume flow and mean blood velocity, which remained elevated longer than the BF induced by 30 Hz. This study demonstrates localized vibrations at 38 Hz and 47 Hz significantly increase BF without affecting the heart rate and may support muscle recovery.

Mechanical Percussion Devices: A Survey of Practice Patterns Among Healthcare Professionals.

Int J Sports Phys Ther. 2021 Jun 2;16(3):766-777. Scott W Cheatham, Russell T Baker, David G Behm, Kyle Stull, Morey J Kolber.

Background: Mechanical percussion devices have become popular among sports medicine professionals. These devices provide a similar effect as manual percussion or tapotement used in therapeutic massage. To date, there are few published studies or evidence-based guidelines for these devices. There is a need to understand what professionals believe about this technology and how they use these devices in clinical practice.

Purpose: To survey and document the knowledge, clinical application methods, and use of mechanical percussion devices among healthcare professionals in the United States.

Design: Cross-sectional survey study.

Methods: A 25-question online survey was emailed to members of the National Athletic Trainers Association, Academy of Orthopedic Physical Therapy, and American Academy of Sports Physical Therapy.

Results: Four hundred twenty-five professionals completed the survey. Most professionals (92%, $n=391$) used devices from two manufacturers: Hyperice® and Theragun®. Seventy-seven percent directed clients to manufacturer and generic websites ($n=329$) to purchase devices. Most respondents used a medium and low device speed setting for pre- and post-exercise (62%, $n=185$), pain modulation (59%, $n=253$), and myofascial mobility (52%, $n=222$). A large proportion of respondents preferred a total treatment time between 30 seconds and three minutes (36-48%, $n=153-204$) or three to five minutes (18-22%, $n=76-93$). Most respondents (54-69%, $n=229-293$) believed that mechanical percussion increases local blood flow, modulates pain, enhances myofascial mobility, and reduces myofascial restrictions. Most respondents (72%, $n=305$) were influenced by other colleagues to use these devices. Sixty-six percent used patient reported outcomes ($n=280$) to document treatment efficacy. Live instruction was the most common mode of education (79%, $n=334$).

Conclusion: These results are a starting point for future research and provide insight into how professionals use mechanical percussion devices. This survey also highlights the existing gap between research and practice. Future research should examine the efficacy of this technology and determine consensus-based guidelines.

Acute Effects of Short-Term Massage Procedures on Neuromechanical Contractile Properties of Rectus Femoris Muscle.

Medicina (Kaunas). 2024 Jan 10;60(1):125. Miloš Dakić, Vladimir Ilić, Lazar Toskić, Sasa Duric, Jožef Šimenko, Milan Marković, Milivoj Dopsaj, Ivan Cuk.

Background and Objectives: In many sports, maintaining muscle work at an optimal level despite fatigue is crucial. Therefore, it is essential to discover the most efficient way of recovery. This study aimed to evaluate and compare the acute effects of four different recovery methods on muscle neuromechanical properties.

Materials and Methods: The research was conducted using a randomized, quasi-experimental, repeated-measures design. Fourteen healthy and active male students of the Faculty of Sport and Physical Education (age 25.1 ± 3.9

years) were included in this study. The tensiomyography was used to evaluate muscle responses after four different types of short-term recovery methods (passive rest, percussive mechanical, vibro-mechanical, and manual massage) on the rectus femoris muscle on four occasions: baseline, post fatigue, post recovery and prolonged recovery.

Results: The ANOVA revealed that muscle fatigue decreased maximal vertical muscle displacement (Dm) and muscle contraction time (Tc) in post fatigue compared to the baseline. The most important finding shows that only the vibro-mechanical massage resulted in an increase in Tc in the prolonged recovery compared to the post fatigue ($p = 0.028$), whereas only manual massage showed no differences in Dm from the baseline in post-recovery ($p = 0.148$). Moreover, both manual and vibro-mechanical massages increased Dm and Tc in prolonged recovery, indicating no differences from the baseline (all $p > 0.05$), thus showing signs of muscle recovery. Percussion mechanical massage and passive rest did not show indices of muscle recovery.

Conclusions: Manual massage could induce immediate positive changes in Dm by reducing muscle stiffness. In addition, vibro-mechanical and manual massage improved muscle tissue by rapidly returning Dm and Tc values to baseline at prolonged recovery measurement (5 min after the fatigue protocol). These findings can benefit sports practitioners, and physical therapists in developing the best recovery method after muscle fatigue.

Acute Effects of Percussive Massage Therapy on Thoracolumbar Fascia Thickness and Ultrasound Echo Intensity in Healthy Male Individuals: A Randomized Controlled Trial.

Int J Environ Res Public Health. 2024 Nov 28;21(12):1585. Yang C, Huang X, Li Y, Sucharit W, Sirasaporn P, Eungpinichpong W.

Percussive massage therapy (PT) has been widely used by therapists and the fitness population to treat myofascial-related conditions. However, there is no evidence to confirm the effects of PT on the fascia. This study aimed to investigate the effects of PT on thoracolumbar fascia (TLF) morphology and other related outcomes.

Methods: Sixty-six healthy males participated and were randomly allocated into a percussive massage group (PT group) and a control group. The PT group received 15 min of back percussion massage, while the control group rested prone lying in the same environment for 15 min. Thoracolumbar fascia (TLF) thickness and echo intensity, perceived stiffness, lumbar flexibility, and skin temperature were measured in both groups before and immediately after the intervention.

Result: TLF thickness and lumbar flexibility did not change when compared in the two groups. However, the echo intensity (left side, difference -3.36, 95% CI -5.1 to -1.6; right side, difference -4.39, 95% CI -6.1 to -2.7) and perceived stiffness (difference, -1.18, 95% CI -1.84 to -0.52) in the TLF region were significantly lower in the PT group than in the control group and were accompanied by increased skin temperature (difference 0.29, 95% CI 0.11 to 0.48).

Conclusion: We suggest that a 15 min PT with 30 Hz on the back region could reduce TLF echo intensity and perceived stiffness and increase skin temperature in healthy men individual.

The impact of protocol designs for using massage guns on lower body flexibility: A randomised cross-over design study.

J Bodyw Mov Ther. 2025 Mar;41:85-93. Lorna Sams, Ben L Langdown, Joan Simons, Jitka Vseteckova.

Introduction: Current protocols for delivering percussive therapy (PT) using massage guns are heterogeneous creating a need to establish the impact of study design on physiological measures. This cross-over design study aimed to determine the most effective protocol, among the eight protocols examined, on lower body flexibility, and to support the provision of protocol validation for future research.

Method: Recreationally active healthy adults ($n = 35$) undertook two main protocols; three sessions per week at 2100 rpm or increasing the speed from session-to-session: 1750 to 2100-2400 rpm. PT was applied for 60 s to each of the quadriceps, gluteals, hamstrings and calves of both legs. Paired-samples t-tests assessed pre- and post-intervention data for hip flexion and ankle dorsi-flexion range of motion (ROM). These were collected in all sessions using a digital goniometer allowing changes for eight different protocols to be examined.

Results: Results showed the most effective protocol, among the eight protocols examined, for achieving significant gains in lower body flexibility is applying massage gun PT three times a week with increased speeds across sessions (1750-2100-2400 rpm), with average increases for the combined dominant and non-dominant legs of 5.8% for hip flexion and 5.6% ankle dorsiflexion.

Conclusions: Practitioners and the public using this protocol could target specific improvements in hip flexion and ankle dorsi-flexion ROM and researchers may wish to adopt this protocol to allow homogenous analysis across study populations in future research.

Acute Effects of a Percussive Massage Treatment on Movement Velocity during Resistance Training.

Int J Environ Res Public Health. 2021 Jul 21;18(15):7726. Manuel García-Sillero, Jose Manuel Jurado-Castro, Javier Benítez-Porres, Salvador Vargas-Molina.

The aim of this research was to verify whether the application of percussion therapy during inter-set rest periods increases the number of repetitions performed before reaching a 30% velocity loss threshold during a bench press exercise.

Methods: Twenty-four male university students participated in this study (24.3 ± 1.3 years; 77.5 ± 8.3 kg; 177.0 ± 5.6 cm; 24.7 ± 2.6 kg·m⁻²). Participants were randomized into two groups: a percussion therapy group (PTG) and a control group (CG). They performed 4 sets at 70% of a one-repetition maximum before reaching a 30% velocity loss threshold with an inter-set recovery of 3 min.

Results: The PTG performed a greater total number of repetitions compared to the CG (44.6 ± 4.8 vs. 39.5 ± 6.8 ; $p = 0.047$; ES = 0.867). No differences were observed for the different movement velocity variables and fatigue control ($p > 0.05$).

Conclusions: Percussion therapy is an effective method to delay the loss of movement velocity in the bench press exercise.

The Acute Effects of Theragun™ Percussive Therapy on Viscoelastic Tissue Dynamics and Hamstring Group Range of Motion.

J Sports Sci Med. 2023 Sep 1;22(3):496-501. Brendon Skinner, Lauren Dunn, Richard Moss.

Handheld percussive therapy (PT) massage guns have seen a rapid rise in use and with it increased attention within injury prevention and sport performance settings. Early studies have proposed beneficial effects upon range of motion (ROM), however the mechanism behind these increases remains unreported. This study aimed to determine the influence of a minimal frequency PT dose upon ROM and myotonometry outcomes. Twenty participants (N = 20; 13 males and 7 females, height $1.78\text{cm} \pm 9.62$; weight $77.35\text{kg} \pm 8.46$) participants were allocated to either a PT group receiving 2 x 60-seconds (plus 30-seconds rest) via a Theragun™ Pro4 to the hamstrings covering a standardised 20 lengths from proximal to distal via the standard ball attachment at 1 bar of pressure or a control group (CON) of 2-minutes 30-seconds passive supine rest. Pre and post intervention outcomes were measured for ROM via passive straight leg raise (PSLR) and tissue dynamics via MyotonPro (Tone, Stiffness, Elasticity, Relaxation Time). Results showed significant within-group increases ($p < 0.0001$, η^2 0.656, +11.4%) in ROM following PT and between group difference against CON ($P < 0.026$). Significant within-group differences in stiffness ($p < 0.016$, η^2 0.144, -6%), tone ($p < 0.003$, η^2 0.213, +2%) and relaxation time ($p < 0.002$, η^2 0.232, +6.3%) were also reported following PT. No significant difference was reported in elasticity ($P > 0.05$) or any other between group outcomes. PT therapy can provide an acute increase in hamstring group ROM following a resultant decrease in tissue stiffness.

Percussive Massage Improved Quadriceps Pain Intensity, Fatigue, and Perceived Recovery After Habitual Running but had No Effect on Vertical Jump: Randomized Trial.

Clin J Sport Med. 2025 Mar 26;35(4):431-434. Bruno Soares Alves, Larissa Oliveira Barbieri Coutinho, Raphael Oliveira Caetano, Fernanda de Oliveira Lauria, Diogo Simões Fonseca, Diogo Carvalho Felício.

Objective: The objective of this study was to evaluate whether percussive massage reduces the intensity of quadriceps pain and perceived fatigue and improves perceived recovery and vertical jump after habitual running.

Design: Randomized clinical trial.

Settings: Road race.

Participants: Eighty-four runners aged 18 to 60 years, 1-year experience in running and a training frequency of twice a week, were included (experimental group: $n = 39$, 34.33 ± 1.61 years, 61% M, 5.68 ± 1.16 years of running experience; control group: $n = 45$; 34.51 ± 1.50 years; 71% M; 6.01 ± 1.02 years of running experience).

Interventions: The experimental group received 10 minutes of percussive massage on the quadriceps, and the control group received sham hip and knee joint mobilization.

Main outcome measures: Quadriceps pain intensity and fatigue (visual analog scale), perceived recovery (perceived global effect scale), and vertical jump after habitual running.

Results: The experimental group showed better results for quadriceps pain intensity (0.98; 95% confidence interval [CI], -1.63 to -0.34), fatigue (0.7; 95% CI, -1.45 to -0.05) and perceived recovery (0.54; 95% CI, 0.02-1.07), but not for vertical jump performance (0.95; 95% CI, -1.57-3.47).

Conclusions: Percussive massage improved pain intensity, fatigue, and perceived recovery after running but had no effect on vertical jump.

In vivo transient vibration assessment of the normal human thoracolumbar spine

J Manipulative Physiol Ther. 2000 Oct;23(8):521-30. T S Keller, C J Colloca, A W Fuhr

Objective: The objective of this study was to quantify the mobility characteristics (dynamic stiffness and mechanical impedance) of the normal human thoracolumbar spine with a transient vibration analysis technique.

Design: This study is a prospective clinical investigation to obtain normative biomechanical data from the human male and female spine in vivo.

Setting: Musculoskeletal research laboratory, university setting.

Subjects: Twenty asymptomatic subjects (age range, 20-60 years) with no recent history of musculoskeletal complaints.

Main outcome measures: Mechanical impedance, effective stiffness, and resonant frequency analyses were used to quantify the dynamic stiffness of the thoracolumbar spine in this subject population. Data were obtained from posteroanterior mechanical thrusts delivered with an activator adjusting instrument equipped with a load cell and accelerometer by means of a portable computer.

Results: In response to the activator adjusting instrument thrusts, the thoracolumbar spine typically exhibited an impedance minimum at frequencies ranging between 30 and 50 Hz. The maximum posteroanterior impedance and corresponding maximum effective stiffness of the thoracolumbar spine and sacrum was roughly 2 to 8 times greater than the magnitude of the impedance minimum. Statistically significant differences in mobility between male and female subjects were noted, particularly for frequencies corresponding to the maximum mobility (40 Hz) and minimum mobility (10-20 Hz, 70-80 Hz). For most subjects (both male and female), the lumbar region exhibited a higher impedance and stiffness (less mobility) when compared with the thoracic region.

Conclusions: The posteroanterior mechanical behavior of the human thoracolumbar spine was found to be sensitive to mechanical stimulus frequency and showed significant region-specific and gender differences. In the frequency range of 30 to 50 Hz, the lumbar spine of this subject population is the least stiff and therefore has the greatest mobility. From a biomechanical point-of-view, the results of this study indicate that dynamic spinal manipulative therapy procedures will produce more spinal motion for a given force, particularly when the posteroanterior manipulative thrust is delivered in frequency ranges at or near the resonant frequency. In this regard, spinal manipulative therapy procedures designed to target the resonant frequency of the spine require less force application. Both magnitude and frequency content of manual and mechanical thrusting manipulations may be critical elements for therapeutic outcome.

History and Evolution of the Tuning Fork.

Cureus. 2024 Jan 1;16(1):e51465. Keerthi Eraniyan, Latha Ganti.

During the early twentieth century early years, tuning forks found new applications in medicine when they were used to stimulate "vibration sense" on bony prominences. Vibration sense is the basic feeling of vibration against bone. This method, recognized as a crude test for neural pathways used in proprioception, which enables us to perceive body part location, movement, and action, was a concept developed by Landry, Bell, Bastian, Ferrier, and others during the nineteenth century. It played a vital role in diagnosing sensory and posterior column nerve disorders.

Subluxation:

The Chiropractic Vertebral Subluxation Part 9: Complexes, Models, and Consensus From 1979 to 1995.

J Chiropr Humanit. 2019 Apr 6;25:130–145. Simon A Senzon

In describing the hypothesis, J. D. Grostic addressed the literature in relation to what was known about dentate ligament attachments to vertebra in 1988 and other ways the ligament may distort the cord. He built upon previous research from B. J. Palmer's cord pressure model; the upper cervical approaches developed by J. F. Grostic, Gregory, and Sweat; as well as the Breig paradigm of adverse mechanical cord tension. J. D. Grostic proposed that the neurological significance of this hypothesis would help to explain many clinical phenomena commonly found by upper cervical practitioners, which may be related to the upper cervical cord in relation to spinal-thalamic tracts and neurological structures.

Indications for spinal manipulation in the treatment of back pain.

ACA J Chiropr. 1982;19(10):51–52. Gatterman M

The localized effects of such manipulation may be normalization of joint mobility and nerve function, in addition to pain reduction, with frequent compensatory changes in other areas of spinal function. The secondary effects can include changes in peripheral neurological function and may include relief from somatic pain syndromes, nerve compression syndromes, functional disorders of visceral origin, autonomic pain syndromes and psycho-somatic syndromes.

Faye included 5 components in his model: biomechanical, neurological, muscular, inflammatory, and the stress response. He wrote:

In 1967 at the Anglo- European Chiropractic College I developed class notes that quoted the following authors: Breig, Janda, Lewitt, Illi, Gillet, Wyke, Grice, Mennell, Sandoz, Homewood, Selye, Panjabi, White, and many others that were references for the subluxation complex model. The art of marrying the biomechanical, neurobiological, pathological, musculoskeletal, inflammatory and stress related research into a uniquely chiropractic paradigm was a challenge to say the least.

Faye described the CVS as "a complex clinical entity," comprising pathophysiological changes associated with "one or more of the following: Neuropathophysiology, Kinesiopathology, Myopathology, Histopathology, and Biochemical".

The subluxation has just recently been re-defined by the Rubicon Group and states:

"We currently define a chiropractic subluxation as a self-perpetuating, central segmental motor control problem that involves a joint, such as a vertebral motion segment, that is not moving appropriately, resulting in ongoing maladaptive neural plastic changes that interfere with the central nervous system's ability to self-regulate, self-organize, adapt, repair and heal."

The Definition of Subluxation.

https://chiro.org/Subluxation/The_Definition_of_Subluxation.shtml Compiled by Frank M. Painter, D.C.

The 5 Component "Vertebral Subluxation Complex" Model

Source – Lantz or Flesia?

Kinesiopathology – spinal pathomechanics, including alignment and motion irregularities, involving:

- Hypomobility, segmental blockade, fixation: Abnormal restriction of joint motion, OR
- Hypermobility: Abnormal increase in joint motion.
- Compensation reaction: Long term hypomobility causes the joint above the hypomobile area and occasionally the joint below to become hypermobile.
- Loss of joint play: The loss of normal vertical "joint slack/play" so that the joint becomes hypomobile on the vertical plane.
- Loss of central axis of motion: The loss of normal "Joint Slack/play" so that the joint becomes hypomobile on the rotational joint plane.
- Positional dyskinesia, dynamic misalignment: Joint misalignment throughout the entire range of motion of the involved joint.

Neuropathophysiology, Neuropathology – compressed or facilitated nerve tissue, involving:

- Compressive lesion, the pinched nerve, neurological hypoactivity: The literature indicates that of the neurological damage induced by spinal kinesiopathologic changes, about 10–15% results in a compressive profile.
- Facilitative lesion, the facilitative segment, neurological irritation, neurological hyperactivity: The literature indicates that, of the neurological damage induced by spinal kinesiopathologic changes, about 85–90% results in a facilitated profile.
- Articular neuropathy, the hyaline cartilage pads in the diarthrodial spinal joints as well as the local articular ligamentous support tissue are seriously stressed during an acute episode of the vertebral subluxation complex and more so in long term uncorrected vertebral subluxation complex episodes. This causes, in addition to the histopathologically induced pathoanatomical changes due to long term uncorrected vertebral subluxation complex, significant damage to the balance and proprioceptive nerve endings (the Type I Mechano receptors, Type II & III Articular Receptors and Type IV Nociceptive 'Pain' Receptors) in the articular surfaces and the capsular ligaments so that "Noxious" nerve impulses are fired off afferently back to the spinal balance center in the cerebellum, the proprioceptor center in the cerebral cortex and in the Limbic 'joint pain' regions of the cerebral cortex. Surprisingly, the spinal cord stores facilitated data also, causing reflexogenic activity from the involved joint.

Myopathology – muscle spasm, muscle weakness/ atrophy involving:

1. From the compressive lesion:
 - Neurological hypoactivity
 - Hypotonus
 - Atrophy
 - Fibrosis
2. From the facilitative lesion:
 - Neurological hyperactivity
 - Hypertonus
 - Spasm
 - Fibrosis (see above)
3. From articular neuropathy
 - "Erroneous" adaptation responses
 - Adaptive spasm and weakness
 - Resulting fibrous tissue (see above)

Histopathology – inflammation, edema and swelling of tissue, usually local to the traumatized area, involving:

- Basically, histopathology is to be considered as the entire range of the inflammatory process. Uncorrected, this leads to fibrotic degeneration. In some cases, this degenerative process leads to calcific salt deposition within the fibrous lattice. The literature presents three phases of fibrotic/ calcific ligamentous degeneration.
- Phase 1 – The original sprain.
- Phase 2 – The beginnings of fibrosis.
- Phase 3 – Complete fibrosis. Complete fibroses and the beginnings of fibrosis are not reversible, leading to permanent spinal biomechanical impairment. Bone degeneration is considered under component #5.

Pathophysiology, Pathology, Biochemical Changes – pathophysiologic and pathoanatomical changes due to the previous four components usually seen locally as degeneration, fibrous tissue and/or erosion local and peripherally as a loss of global homeostasis.

- Local to the spine:
 - Bone degeneration – Bone and soft tissue degeneration is an inevitable consequence of uncorrected spinal trauma (micro or macro) and to a degree, a result of a shifting postural alignment to gravity.
 - Bone regeneration – A normal physiologic phenomenon. Bone regeneration alters architectural outlines of bone when the involved bone tissue becomes chronically out of alignment with gravity. This can be seen on spinal x-rays and is usually confused with the spinal degenerative process.

Lantz has since revised and expanded the “vertebral subluxation complex” model to include nine components:

1. Kinesiology
2. Neurology
3. Myology
4. Connective Tissue Physiology
5. Angiology
6. Inflammatory Response
7. Anatomy
8. Physiology
9. Biochemistry

Gate Control and the Neural Matrix:

Suggested viewing: DR MELZACK Interviewed on Gate Control Theory by Dr Leora Kuttner April 1989

<https://youtu.be/0qGZPmUttUk?si=IB5FmNvNotUrnER5>

Suggested viewing: The Gate Control Theory of Pain/ Ronald Melzack

<https://youtu.be/IXkn6NoLPtU?si=Fqf1m7VP1by1piCN>

PKC γ interneurons, a gateway to pathological pain in the dorsal horn.

J Neural Transm (Vienna). 2020 Apr;127(4):527-540. Alain Artola, Daniel Voisin, Radhouane Dallel.

Chronic pain is a frequent and disabling condition that is significantly maintained by central sensitization, which results in pathological amplification of responses to noxious and innocuous stimuli. As such, mechanical allodynia, or pain in response to a tactile stimulus that does not normally provoke pain, is a cardinal feature of chronic pain. Recent evidence suggests that the dorsal horn excitatory interneurons that express the γ isoform of protein kinase C (PKC γ) play a critical role in the mechanism of mechanical allodynia during chronic pain. Here, we review this evidence as well as the main aspects of the development, anatomy, electrophysiology, inputs, outputs, and pathophysiology of dorsal horn PKC γ neurons. Primary afferent high-threshold neurons transmit the nociceptive message to the dorsal horn of the spinal cord and trigeminal system where it activates second-order nociceptive neurons relaying the information to the brain. In physiological conditions, low-threshold mechanoreceptor inputs activate inhibitory interneurons in the dorsal horn, which may control activation of second-order nociceptive neurons. During chronic pain, low-threshold mechanoreceptor inputs now activate PKC γ neurons that forward the message to second-order nociceptive neurons, turning thus tactile inputs into pain. Several mechanisms may contribute to opening this gate, including disinhibition, activation of local astrocytes, release of diffusible factors such as reactive oxygen species, and alteration of the descending serotonergic control on PKC γ neurons through 5-HT_{2A} serotonin receptors. Dorsal horn PKC γ neurons, therefore, appear as a relevant therapeutic target to alleviate mechanical allodynia during chronic pain.

Spinal mechanisms of acute and persistent pain.

Reg Anesth Pain Med. 1999 Jan-Feb;24(1):59-67. A I Basbaum.

Although there is considerable information about the mechanisms through which injury stimuli produce acute pain, recent studies indicate that there are significant long-term consequences of persistent injury. Pain is exacerbated, in part, because of a reorganization of spinal cord circuitry in the setting of persistent injury. This review describes our studies of the contribution of the primary afferent neurotransmitter, substance P (SP), to these changes. By following internalization of the SP receptor in spinal cord dorsal horn neurons, we have identified the stimuli that evoke SP release and the neurons that respond to these stimuli. Importantly, based on the intensities of stimuli required to evoke internalization, we conclude that SP is only released under conditions in which severe pain would be produced, that the release can be evoked by intense stimulation of somatic and visceral tissue, and that multiple stimulus modalities are effective. We also found that the numbers of neurons that are influenced increases dramatically in the setting of inflammation. Using a knockout strategy, we have also raised mice with a deletion of the preprotachykinin-A (PPT-A) gene, which encodes for SP and neurokinin A (NKA), and have identified a specific behavioral phenotype in which the animals do not detect a window of “pain” intensities; this window cuts across stimulus modalities. These results provide an important behavioral correlate of the receptor internalization studies. On the other hand, the allodynia (lowered pain threshold) that occurs in the setting of injury was not altered in these animals. Among the factors that could underlie injury-induced allodynia are the second messenger systems that are activated in dorsal horn neurons.

Our studies have recently implicated the gamma isoform of protein kinase C (PKCgamma) in the development of nerve injury-induced neuropathic pain. Specifically, we found that although acute pain responses of mice with a deletion of PKCgamma are not altered, partial injury to the sciatic nerve (which induces a severe thermal and mechanical allodynia in the wild type mouse) is without effect in the knockout. Furthermore, the anatomical/neurochemical reorganization that typically follows sciatic nerve section does not occur in the PKCgamma mutant mice. Because the spinal cord distribution of interneurons that express PKCgamma is concentrated almost exclusively in the inner part of lamina II, we believe that changes in the properties of these neurons are key to the development of nerve injury-induced neuropathic pain conditions. Taken together, these studies emphasize that **persistent pain should be considered a disease state of the nervous system**, not merely a symptom of some other disease conditions. **In the setting of persistent injury, the nervous system undergoes dramatic changes that exacerbate and prolong the pain condition.** Our studies underscore the importance of preventing the long-term changes that result from persistent injury.

Spinal cord mechanisms of chronic pain and clinical implications.

Curr Pain Headache Rep. 2010 Jun;14(3):213-20. Hsinlin Thomas Cheng.

Chronic pain is a prevalent and challenging problem for most medical practitioners. Because of the complex pathologic mechanisms involved in chronic pain, optimal treatment is still under development. **The spinal cord is an important gateway for peripheral pain signals transmitted to the brain. In chronic pain states, painful stimuli trigger afferent fibers in the dorsal horn to release neuropeptides and neurotransmitters.** These events induce multiple inflammatory and neuropathic processes in the spinal cord dorsal horn, and trigger modification and plasticity of local neural circuits. As a result, ongoing noxious signals to the brain are amplified and prolonged, a phenomenon known as central sensitization. In this review, the molecular events associated with central sensitization, as well as their clinical implications, are discussed.

Pathophysiology of neuropathic pain: molecular mechanisms underlying central sensitization in the dorsal horn in neuropathic pain.

Brain Nerve. 2012 Nov;64(11):1255-65. Hiroki Yamanaka, Koichi Noguchi.

Neuropathic pain syndromes are clinically characterized by spontaneous pain and evoked pain (hyperalgesia and allodynia). The optimal treatment approach for neuropathic pain is still under development because of the complex pathological mechanisms underlying this type of pain. **The spinal cord is an important gateway thorough which peripheral pain signals are transmitted to the brain, and sensitization of the spinal neurons is one of the important mechanisms underlying neuropathic pain.** Central sensitization represents enhancement of the function of neuronal circuits in nociceptive pathways and is a manifestation of the remarkable plasticity of the somatosensory nervous system after nerve injury. This review highlights the pathological features of central sensitization, which develops because of (1) injury-induced abnormal inputs from primary afferents, (2) increase in the excitability of dorsal horn neurons, and (3) activated glial cell-derived signals.

Pain and the neuromatrix in the brain.

J Dent Educ. 2001 Dec;65(12):1378-82. R Melzack.

The neuromatrix theory of pain proposes that pain is a multidimensional experience produced by characteristic "neurosignature" patterns of nerve impulses generated by a widely distributed neural network – the "body-self neuromatrix" – in the brain. These neurosignature patterns may be triggered by sensory inputs, but they may also be generated independently of them. Acute pains evoked by brief noxious inputs have been meticulously investigated by neuroscientists, and their sensory transmission mechanisms are generally well understood. In contrast, chronic pain syndromes, which are often characterized by severe pain associated with little or no discernible injury or pathology, remain a mystery. Furthermore, chronic psychological or physical stress is often associated with chronic pain, but the relationship is poorly understood. **The neuromatrix theory of pain provides a new conceptual framework to examine these problems. It proposes that the output patterns of the body-self neuromatrix activate perceptual, homeostatic, and behavioral programs after injury, pathology, or chronic stress.** Pain, then, is produced by the output of a widely distributed neural network in the brain rather than directly by sensory input evoked by injury, inflammation, or other pathology. The neuromatrix, which is genetically determined and modified by sensory experience, is the primary mechanism that generates the neural pattern that produces pain. Its output pattern is determined by multiple influences, of which the somatic sensory input is only a part, that converge on the neuromatrix.

From the gate to the neuromatrix.

Pain. 1999 Aug;Suppl 6:S121-S126. Ronald Melzack.

The gate control theory's most important contribution to understanding pain was its emphasis on central neural mechanisms. **The theory forced the medical and biological sciences to accept the brain as an active system that filters, selects and modulates inputs. The dorsal horns, too, were not merely passive transmission stations but sites at which dynamic activities (inhibition, excitation and modulation) occurred.** The great challenge ahead of us is to understand brain function. I have therefore proposed that the brain possesses a neural network – the body-self neuromatrix – which integrates multiple inputs to produce the output pattern that evokes pain. The body-self neuromatrix comprises a widely distributed neural network that includes parallel somatosensory, limbic and thalamocortical components that subserve the sensory-discriminative, affective-motivational and evaluative-cognitive

dimensions of pain experience. The synaptic architecture of the neuromatrix is determined by genetic and sensory influences. The 'neurosignature' output of the neuromatrix – patterns of nerve impulses of varying temporal and spatial dimensions – is produced by neural programs genetically built into the neuromatrix and determines the particular qualities and other properties of the pain experience and behavior. Multiple inputs that act on the neuromatrix programs and contribute to the output neurosignature include. (1) sensory inputs (cutaneous, visceral and other somatic receptors); (2) visual and other sensory inputs that influence the cognitive interpretation of the situation; (3) phasic and tonic cognitive and emotional inputs from other areas of the brain; (4) intrinsic neural inhibitory modulation inherent in all brain function; (5) the activity of the body's stress-regulation systems, including cytokines as well as the endocrine, autonomic, immune and opioid systems. We have traveled a long way from the psychophysical concept that seeks a simple one-to-one relationship between injury and pain. We now have a theoretical framework in which a genetically determined template for the body-self is modulated by the powerful stress system and the cognitive functions of the brain, in addition to the traditional sensory inputs.

Tensegrity and Piezoelectricity:

From tensegrity to human organs-on-chips: implications for mechanobiology and mechanotherapeutics.

Biochem J. 2023 Feb 27;480(4):243-257. Donald E Ingber.

The field of mechanobiology, which focuses on the key role that physical forces play in control of biological systems, has grown enormously over the past few decades. Here, I provide a brief personal perspective on the development of the tensegrity theory that contributed to the emergence of the mechanobiology field, the key role that crossing disciplines has played in its development, and how it has matured over time. I also describe how pursuing questions relating to mechanoechemical transduction and mechanoregulation can lead to the creation of novel technologies and open paths for development of new therapeutic strategies for a broad range of diseases and disorders.

Tensegrity, cellular biophysics, and the mechanics of living systems.

Rep Prog Phys. 2014 Apr;77(4):046603. Donald E Ingber, Ning Wang, Dimitrije Stamenovic.

The recent convergence between physics and biology has led many physicists to enter the fields of cell and developmental biology. One of the most exciting areas of interest has been the emerging field of mechanobiology that centers on how cells control their mechanical properties, and how physical forces regulate cellular biochemical responses, a process that is known as mechanotransduction. In this article, we review the central role that tensegrity (tensional integrity) architecture, which depends on tensile prestress for its mechanical stability, plays in biology. We describe how tensional prestress is a critical governor of cell mechanics and function, and how use of tensegrity by cells contributes to mechanotransduction. Theoretical tensegrity models are also described that predict both quantitative and qualitative behaviors of living cells, and these theoretical descriptions are placed in context of other physical models of the cell. In addition, we describe how tensegrity is used at multiple size scales in the hierarchy of life – from individual molecules to whole living organisms – to both stabilize three-dimensional form and to channel forces from the macroscale to the nanoscale, thereby facilitating mechanoechemical conversion at the molecular level.

Tensegrity-based mechanosensing from macro to micro.

Prog Biophys Mol Biol. 2008 Jun-Jul;97(2-3):163-79. Donald E Ingber.

This article is a summary of a lecture on cellular mechanotransduction that was presented at a symposium on "Cardiac Mechano-Electric Feedback and Arrhythmias" that convened at Oxford, England in April 2007. Although critical mechanosensitive molecules and cellular components, such as integrins, stretch-activated ion channels, and cytoskeletal filaments, have been shown to contribute to the response by which cells convert mechanical signals into a biochemical response, little is known about how they function in the structural context of living cells, tissues and organs to produce orchestrated changes in cell behavior in response to stress. Here, studies are reviewed that suggest our bodies use structural hierarchies (systems within systems) composed of interconnected extracellular matrix and cytoskeletal networks that span from the macroscale to the nanoscale to focus stresses on specific mechanotransducer molecules. A key feature of these networks is that they are in a state of isometric tension (i.e., experience a tensile prestress), which ensures that various molecular-scale mechanoechemical transduction mechanisms proceed simultaneously and produce a concerted response. These features of living architecture are the same principles that govern tensegrity (tensional integrity) architecture, and mathematical models based on tensegrity are beginning to provide new and useful descriptions of living materials, including mammalian cells. This article reviews how the use of tensegrity at multiple size scales in our bodies guides mechanical force transfer from the macro to the micro, as well as how it facilitates conversion of mechanical signals into changes in ion flux, molecular binding kinetics, signal transduction, gene transcription, cell fate switching and developmental patterning.

Tensegrity and mechanoregulation: from skeleton to cytoskeleton.

Osteoarthritis Cartilage. 1999 Jan;7(1):81-94. C S Chen, D E Ingber.

Objective: To elucidate how mechanical stresses that are applied to the whole organism are transmitted to individual cells and transduced into a biochemical response.

Design: In this article, we describe fundamental design principles that are used to stabilize the musculoskeletal system at many different size scales and show that these design features are embodied in one particular form of architecture that is known as tensegrity.

Results: Tensegrity structures are characterized by use of continuous tension and local compression; architecture, prestress (internal stress prior to application of external force), and triangulation play the most critical roles in terms of determining their mechanical stability. In living organisms, use of a hierarchy of tensegrity networks both optimizes structural efficiency and provides a mechanism to mechanically couple the parts with the whole: mechanical stresses applied at the macroscale result in structural rearrangements at the cell and molecular level.

Conclusion: Due to use of tensegrity architecture, mechanical stress is concentrated and focused on signal transducing molecules that physically associate with cell surface molecules that anchor cells to extracellular matrix, such as integrins, and with load-bearing elements within the internal cytoskeleton and nucleus. Mechanochemical transduction may then proceed through local stress-dependent changes in molecular mechanics, thermodynamics, and kinetics within the cell. In this manner, the entire cellular response to stress may be orchestrated and tuned by altering the prestress in the cell, just as changing muscular tone can alter mechanical stability and structural coordination throughout the whole musculoskeletal system.

Tensegrity: the architectural basis of cellular mechanotransduction.

Annu Rev Physiol. 1997;59:575-99. D E Ingber.

Physical forces of gravity, hemodynamic stresses, and movement play a critical role in tissue development. Yet, little is known about how cells convert these mechanical signals into a chemical response. This review attempts to place the potential molecular mediators of mechanotransduction (e.g. stretch-sensitive ion channels, signaling molecules, cytoskeleton, integrins) within the context of the structural complexity of living cells. The model presented relies on recent experimental findings, which suggests that cells use tensegrity architecture for their organization. Tensegrity predicts that cells are hard-wired to respond immediately to mechanical stresses transmitted over cell surface receptors that physically couple the cytoskeleton to extracellular matrix (e.g. integrins) or to other cells (cadherins, selectins, CAMs). Many signal transducing molecules that are activated by cell binding to growth factors and extracellular matrix associate with cytoskeletal scaffolds within focal adhesion complexes. Mechanical signals, therefore, may be integrated with other environmental signals and transduced into a biochemical response through force-dependent changes in scaffold geometry or molecular mechanics. Tensegrity also provides a mechanism to focus mechanical energy on molecular transducers and to orchestrate and tune the cellular response.

Tensegrity and mechanotransduction.

J Bodyw Mov Ther. 2008 Jul;12(3):198-200. Donald E Ingber.

Anyone who is skilled in the art of physical therapy knows that the mechanical properties, behavior and movement of our bodies are as important for human health as chemicals and genes. However, only recently have scientists and physicians begun to appreciate the key role which mechanical forces play in biological control at the molecular and cellular levels. This article provides a brief overview of a lecture presented at the First International Fascia Research Congress that convened at Harvard Medical School in Boston, MA on October 4, 2007. In this lecture, I described what we have learned over the past 30 years as a result of our research focused on the molecular mechanisms by which cells sense mechanical forces and convert them into changes in intracellular biochemistry and gene expression - a process called "mechanotransduction". This work has revealed that molecules, cells, tissues, organs, and our entire bodies use "tensegrity" architecture to mechanically stabilize their shape, and to seamlessly integrate structure and function at all size scales. Through the use of this tension-dependent building system, mechanical forces applied at the macroscale produce changes in biochemistry and gene expression within individual living cells. This structure-based system provides a mechanistic basis to explain how application of physical therapies might influence cell and tissue physiology.

Life on the wire: on tensegrity and force balance in cells.

Acta Biomed. 2005 Apr;76(1):5-12. Carlo Galli, Stefano Guizzardi, Giovanni Passeri, Guido Maria Macaluso, Renato Scandroglio.

Since cell mechanics has attracted the attention of a growing number of researchers, several models have been proposed to explain cell mechanical behavior, among which tensegrity is certainly the most convincing one. Originally developed by the architect Buckminster Fuller, tensegrity structures are based on the presence of discontinuous compression elements that balance the force generated by continuous tension elements, thus reaching an equilibrium that is completely independent of gravity. This model is a useful tool to predict cell spreading, motility and especially mechanotransduction, i.e. the capability to transform mechanical stresses into biochemical responses, a key process in homeostasis of many tissues that must continuously withstand mechanical forces, like bone, but which is still poorly understood.

Tensegrity II. How structural networks influence cellular information processing networks.

J Cell Sci. 2003 Apr 15;116(Pt 8):1397-408. Donald E Ingber.

The major challenge in biology today is biocomplexity: the need to explain how cell and tissue behaviors emerge from collective interactions within complex molecular networks. Part I of this two-part article, described a mechanical model of cell structure based on tensegrity architecture that explains how the mechanical behavior of the cell emerges from physical interactions among the different molecular filament systems that form the cytoskeleton. Recent work shows that the cytoskeleton also orients much of the cell's metabolic and signal transduction machinery and that mechanical distortion of cells and the cytoskeleton through cell surface integrin receptors can profoundly affect cell behavior. In

particular, gradual variations in this single physical control parameter (cell shape distortion) can switch cells between distinct gene programs (e.g. growth, differentiation and apoptosis), and this process can be viewed as a biological phase transition. Part II of this article covers how combined use of tensegrity and solid-state mechanochemistry by cells may mediate mechanotransduction and facilitate integration of chemical and physical signals that are responsible for control of cell behavior. In addition, it examines how cell structural networks affect gene and protein signaling networks to produce characteristic phenotypes and cell fate transitions during tissue development.

Tensegrity I. Cell structure and hierarchical systems biology.

J Cell Sci. 2003 Apr 1;116(Pt 7):1157-73. Donald E Ingber.

In 1993, a Commentary in this journal described how a simple mechanical model of cell structure based on tensegrity architecture can help to explain how cell shape, movement and cytoskeletal mechanics are controlled, as well as how cells sense and respond to mechanical forces (J. Cell Sci. 104, 613-627). The cellular tensegrity model can now be revisited and placed in context of new advances in our understanding of cell structure, biological networks and mechanoregulation that have been made over the past decade. Recent work provides strong evidence to support the use of tensegrity by cells, and mathematical formulations of the model predict many aspects of cell behavior. In addition, development of the tensegrity theory and its translation into mathematical terms are beginning to allow us to define the relationship between mechanics and biochemistry at the molecular level and to attack the larger problem of biological complexity. Part I of this two-part article covers the evidence for cellular tensegrity at the molecular level and describes how this building system may provide a structural basis for the hierarchical organization of living systems--from molecule to organism. Part II, which focuses on how these structural networks influence information processing networks, appears in the next issue.

The Architecture of Life.

Scientific American. 1998 Jan;278(1):48-57. Donald Ingber.

NASA: The role of tensegrity in the architecture of organic structures is examined. Topics include a definition of tensegrity, principles of tensegrity applied to the skeleton and cytoskeleton, mechanics in biochemistry, self-assembly of organic structures, geodesic forms in cellular structure, and the universality of the geodesic form.

The Geometry of Anatomy. The Bones of Tensegrity.

<https://intensiondesigns.ca/geometry-of-anatomy/> Tom Flemons.

Among clinicians and bodyworkers today, there appears to be a great deal of interest in the concept of tensegrity as it applies to living forms, but much confusion as well. In some circles it seems to be the flavour of the decade but what are they talking about? What exactly is a tensegrity? Is it a useful scientific description and explanation for anatomical function? Or is it just a metaphor for the intuitive feeling that bodies behave as whole systems held in connective tension? If the latter, it's as good or better than any other analogy and the definition can remain vague. But if tensegrity claims to explain the biomechanics of living structure, then more is required. A clear definition of "biotensegrity" and a means to test the hypothesis is needed. The actual relations between tension and compression components in the body need to be examined. Can biotensegrity help explain the complex interplay of these forces in biomechanical terms and if so what does that imply? One mark of a valid scientific hypothesis is its predictiveness. If tensegrity provides better descriptions, does that make for better prescriptions?

Weaving. Mother of Tensegrity.

<http://www.kennethsnelson.net/icons/struc.htm> Kenneth Snelson.

Weaving and tensegrity share the same grounding principle of alternating helical directions; of left to right; of bypasses clockwise and counterclockwise. In these figures, the column on the left shows the primary weave cells.

Individual tension lines (strings, wires or rope) are attached to the ends of the struts as shown so that each assembly comprises a closed system of tension and compression parts. Each tension line connects individually to the ends of two struts; they do not thread through like strings of beads. The lines are made taut so that they bind the struts, pressing on them as a continuous tension network. The forces introduced by the tightening is permanently stored in the structure, a state known as prestressing.

Open Challenges and Opportunities in Piezoelectricity for Tissue Regeneration.

Adv Sci (Weinh). 2025 Aug 18:e10349. Xiaoling Deng, Yu Zhuang, Jinjie Cui, Liyun Wang, Huilu Zhan, Xudong Wang, Kaili Lin, Changyong Yuan.

Emerging piezoelectric biomaterials have demonstrated their huge potential in diverse medical applications, including ultrasound diagnosis and tissue regeneration. Human body possesses inherent piezoelectricity, producing electrical signal under endogenous load or external pressure to modulate cellular behaviors. Tissue defects caused by traumatic injury will disrupt the electrophysiological microenvironment of the injured area, resulting in unenviable self-healing. Triggered by physical activities or external stimulation, piezoelectric biomaterials exhibit a unique capability to generate electrical fields to restore the electrophysical microenvironment, reprogram cell fate and ultimately facilitate tissue repair. In this review, endogenous piezoelectric substances in the body and tissue piezoelectricity are introduced. Then, the characteristics and piezoelectricity of piezoelectric biomaterials in regenerative medicine are discussed, as well as strategies to prepare novel piezoelectric composites. Moreover, the molecular mechanisms for

the piezoelectric effect on regulating tissue regeneration are systematically summarized. Recent advancements in piezoelectric biomaterials are comprehensively overviewed, including in the regeneration of bone, cartilage, skeletal muscles, tendon, skin, nerve, teeth and periodontal, myocardium, blood vessel and cornea tissues. Finally, the major challenges and future perspectives of piezoelectric biomaterials in regenerative medicine are proposed, hoping to boost the advancement in this promising scientific territory.

Exercise-induced piezoelectric stimulation for cartilage regeneration in rabbits.

Sci Transl Med. 2022 Jan 12;14(627):eabi7282. Yang Liu, Godwin Dzidotor, Thinh T Le, Tra Vinikoor, Kristin Morgan, Eli J Curry, Ritopa Das, Aneesah McClinton, Ellen Eisenberg, Lorraine N Apuzzo, Khanh T M Tran, Pooja Prasad, Tyler J Flanagan, Seok-Woo Lee, Ho-Man Kan, Meysam T Chorsi, Kevin W H Lo, Cato T Laurencin, Thanh D Nguyen.

More than 32.5 million American adults suffer from osteoarthritis, and current treatments including pain medicines and anti-inflammatory drugs only alleviate symptoms but do not cure the disease. Here, we have demonstrated that a biodegradable piezoelectric poly (L-lactic acid) (PLLA) nanofiber scaffold under applied force or joint load could act as a battery-less electrical stimulator to promote chondrogenesis and cartilage regeneration. The PLLA scaffold under applied force or joint load generated a controllable piezoelectric charge, which promoted extracellular protein adsorption, facilitated cell migration or recruitment, induced endogenous TGF- β via calcium signaling pathway, and improved chondrogenesis and cartilage regeneration both in vitro and in vivo. Rabbits with critical-sized osteochondral defects receiving the piezoelectric scaffold and exercise treatment experienced hyaline-cartilage regeneration and completely healed cartilage with abundant chondrocytes and type II collagen after 1 to 2 months of exercise (2 to 3 months after surgery including 1 month of recovery before exercise), whereas rabbits treated with nonpiezoelectric scaffold and exercise treatment had unfilled defect and limited healing. **The approach of combining biodegradable piezoelectric tissue scaffolds with controlled mechanical activation (via physical exercise) may therefore be useful for the treatment of osteoarthritis and is potentially applicable to regenerating other injured tissues.**

Cranio-Spinal-Functional-Meningeal-Unit (CSFMU)

Midline dural filum of the sellar floor: Its relationship to the septum attachment to the sellar floor and the ossification in the sphenoid sinus.

Clin Neurol Neurosurg. 2016 Aug;147:53-8. Yasuhiko Hayashi, Daisuke Kita, Masayuki Iwato, Issei Fukui, Yasuo Sasagawa, Masahiro Oishi, Osamu Tachibana, Mitsutoshi Nakada.

Objectives: It is important to identify and maintain a midline orientation during endoscopic transsphenoidal surgery (ETSS) for sellar lesions to prevent critical injury to the internal carotid artery. Therefore, the preoperative neuroradiological assessment of the bony structures in the sphenoid sinus, including the septum attachment to the sellar floor and its surrounding structures, is essential. It has been reported that the midline filum of the sellar dura can function as a useful intraoperative orientation guide during ETSS. However, the relationship between the midline dural filum and the intrasinus bony structures, such as the sellar floor, the intrasinus septation and the ossification, remains unclear and the mechanisms underlying development of the midline dural filum have also not yet been explored.

Methods: This retrospective study included 160 patients undergoing ETSS to assess both the midline dural filum and the intrasinus bony structures, using video recording reviews. The intrasinus septum and the ossification in the sphenoid sinus were evaluated on the computed tomography images of the bone window.

Results: A midline dural filum was identified in 66 (41.3%) of 160 patients. Attachment of the septum to the sellar midline was found in 61 (39.4%) of 155 patients, after excluding 5 patients with the conchal type of sphenoid sinus, 55 (90.2%) of 61 patients with a septum on the midline and only 6 (6.4%) of the remaining 94 patients without a septum on the midline had a midline dural filum. The relationship between a midline dural filum and a septum on midline was statistically significant ($p < 0.001$), regardless of the number of intrasphenoidal septa. In terms of the types of sphenoid sinus, the midline dural filum was predominantly detected in patients where ossification extended over the midline filum. In patients with the sellar type of sphenoid sinus, 49 (36.0%) of 136 had a midline dural filum, meanwhile, 16 (84.2%) of 19 patients with the pre-sellar type ($p = 0.039$) and all 5 patients (100%) with the conchal type harbored a midline dural filum ($p < 0.001$).

Conclusion: This study clearly verified the importance of the midline dural filum in a large series and evaluated the obvious relationship between the midline dural filum and the bony structures on the sellar floor. Our results strongly suggest that, during developing of the midline dural filum, the sellar dura becomes tethered to the bony elements attached to the sellar surface, such as the septum on the midline and the ossification in both the pre-sellar and the conchal type of sphenoid sinus.

Midline filum of the sellar dura: a useful landmark during endoscopic transsphenoidal pituitary surgery.

Neurosurgery. 2010 Dec;67(2 Suppl Operative):391-4. Gabriel Zada, Albert H Kim, Lance S Governale, Edward R Laws.

Background: During endoscopic transsphenoidal pituitary surgery, identification and constant awareness of the midline is imperative to prevent injury to critical lateral structures, such as the internal carotid arteries.

Objective: To describe the relevance of a midline filum of the sellar dura which, when present, can serve as a useful intraoperative anatomic marker.

Methods: Intraoperative video recordings of twenty patients undergoing endoscopic transsphenoidal surgery were retrospectively reviewed to assess for the presence and location of a midline dural filum or apparent central dural vascular structure. Prospective intraoperative data were gathered on an additional 16 patients.

Results: A midline dural filum was identified in 18 of 36 patients (50%) undergoing endoscopic transsphenoidal surgery. This structure was identified on the midline in all cases, as confirmed by intraoperative neuronavigation and comparison with the vomer. The midline dural filum was identified as a strand-like dural extension (13 patients) or as a small vascular dural structure usually exhibiting low pressure venous bleeding (5 patients). Samples of the midline dural filum were obtained from 2 patients for histopathological analysis, which demonstrated dense collagenous connective tissue without evidence of vessel wall or ductal epithelium.

Conclusion: In addition to anatomic structures such as the vomer and midline sphenoid sinus septations, a midline dural filum serves as a useful marker during the sellar phase of endoscopic transsphenoidal surgery. Along with intraoperative neuronavigation and Doppler ultrasonography of the cavernous carotid arteries, identification of this structure may further aid in safeguarding against injury to critical paramedian structures.

Microanatomy of the dura mater at the craniovertebral junction and spinal region for safe and effective surgical treatment.

J Neurosurg Spine. 2020 Mar 20;33(2):165-171. Kiyoshi Ito, Mitsunori Yamada, Tetsuyoshi Horiuchi, Kazuhiro Hongo.

Objective: Few reports have been published regarding the detailed microsurgical anatomy of the dura mater at the craniovertebral junction (CVJ), although many neurosurgeons have had the opportunity to conduct surgeries in this region, such as in cases of Chiari malformation. The authors aimed to evaluate the detailed and precise microsurgical anatomy of the dura mater at the CVJ for safe and effective surgical treatment at this area.

Methods: This study consisted of dissection of 4 formalin-fixed, continuous, human cadaveric dura maters, extending from the posterior fossa to the C2 level. After removing the occipital bone and C1 laminae, a dural incision was made to harvest the specimen. The following structural and topographical aspects of the dura mater in each region were studied: 1) thickness, 2) morphological characteristics, and 3) vascular structures.

Results: The average thicknesses of the dura mater were $313.4 \pm 137.0 \mu\text{m}$, $3051.5 \pm 798.8 \mu\text{m}$, and $866.5 \pm 359.0 \mu\text{m}$ in the posterior cranial fossa, CVJ, and spinal region, respectively. The outer layer of the posterior cranial dura mater and the tendon of the rectus capitis posterior minor muscle were connected, forming the "myodural bridge." The dura mater at the CVJ had a well-developed vascular network. These vascular structures were determined to be veins or the venous sinus, and were mainly located around the interface between the inner layer of the cranial dura mater and the rectus capitis posterior minor muscle layer. Regarding the morphological features, the bulging located in the inner layer of the dura mater at the CVJ was determined to be the marginal sinus, and contained a pacchionian granulation that allowed for CSF circulation. In the spinal region, the dura mater was characterized by a single, thick layer enclosing the collagen fibers with almost the same orientation.

Conclusions: The dura mater at the CVJ displayed dynamic morphological changes within an extremely short segment. Its characteristic anatomical features were not similar to those in the cranial regions. The dural bulging at the CVJ was determined to be the venous sinus. During surgery in the posterior fossa, CVJ, and spinal cord, different procedures should be used because of the specific microsurgical anatomy of each region.

Anatomic relation between the nuchal ligament (ligamentum nuchae) and the spinal dura mater in the craniocervical region.

Clin Anat. 2002 May;15(3):182-5. N A Dean, B S Mitchell.

There are inconsistencies between the descriptions of the physical connections between the spinal cervical dura and the surrounding tissues. This study was undertaken to clarify the relationship between the spinal dura, the nuchal ligament and the suboccipital muscles. Dissections were performed on embalmed cadavers: in nine the relevant structures were removed en bloc, whereas in one a sagittal section was prepared. In all specimens it was possible to demonstrate continuity in the midline between the nuchal ligament and the posterior spinal dura at the atlanto-occipital and atlanto-axial intervals. No such attachments were found caudal to the arch of the axis. In addition, there was a connective tissue bridge between the deep aspect of the rectus capitis posterior minor muscle to the transverse fibers of the posterior atlanto-occipital membrane that extended laterally to blend with the perivascular tissue of the vertebral arteries. The present study is, we believe, the first to describe continuity between the nuchal ligament and the dura at the atlanto-occipital interspace, and confirms previous descriptions of similar connections at the atlanto-axial level. Knowledge of the exact attachments of the dura may contribute to understanding the biomechanics of the cervical spine and of the possible etiology of some types of cervicogenic headaches.

Attachments of the ligamentum nuchae to cervical posterior spinal dura and the lateral part of the occipital bone.

J Manipulative Physiol Ther. 1998 Mar-Apr;21(3):145-8. B S Mitchell, B K Humphreys, E O'Sullivan.

Objective: To describe previously unrecorded attachments of the ligamentum nuchae to the cervical posterior spinal dura, and to posterolateral parts of the occipital bone in an anatomical study, with particular reference to the deep aspects of the suboccipital triangle and upper cervical region.

Design: Dissections of 10 heads and necks from embalmed cadavers were made in the suboccipital and upper cervical region, either in whole specimens or in parasagittally sectioned specimens.

Results: In parasagittally sectioned material, continuity was observed between the ligamentum nuchae and the posterior cervical spinal dura as the latter passed deeply from the midline toward the dura, but only at the first and second cervical vertebral levels. The ligamentum nuchae also passed bilaterally on to the occipital bone as far as the sutures between the occipital bone and the temporal bones, approaching the inferior nuchal line superiorly.

Conclusion: The present study is the first to describe the full morphology of the relationship between the ligamentum nuchae and the cervical posterior spinal dura and the lateral aspects of the occipital bone. This is of significance for understanding the biomechanics of the cervical spine, particularly rotational movements of the head in the sagittal or transverse planes. This may have implications in manipulative therapy for conditions as cervicogenic headache and for various degenerative disorders affecting the cervical spine.

Configuration of the connective tissue in the posterior atlanto-occipital interspace: a sheet plastination and confocal microscopy study.

Spine (Phila Pa 1976). 2005 Jun 15;30(12):1359-66. Lance Nash, Helen Nicholson, Antonio S J Lee, Gillian M Johnson, Ming Zhang.

Study design: The connective tissue structures in the posterior atlanto-occipital region were investigated using E12 sheet plastinations and confocal microscopy.

Objectives: To define the relationship between rectus capitis posterior minor (RCPm), posterior atlanto-occipital (PAO) membrane, nuchal ligament, and the spinal dura in the PAO interspace.

Summary of background data: It has been speculated that connections between the dura and muscles and/or ligaments in the PAO interspace may transmit forces from the cervical spine joint complexes to the pain-sensitive dura, generating cervicogenic headaches. Anatomic structures involved in these connections include the RCPm, PAO membrane, and nuchal ligament. However, there is little information about the nature of these connections and the relationships between these anatomic structures.

Methods: The study used a combined approach, consisting of the gross anatomic dissection of nine cadavers and the E12 sheet plastination method for thirteen adult human cadavers, five of which were further examined using confocal microscopy.

Results: The study demonstrates that (1) the tendinous fibers from the medial and deep part of the RCPm muscle are continuous antero-inferiorly with the spinal dura; (2) the PAO membrane is part of the RCPm fascia and tendon and the perivascular sheathes; (3) antero-inferiorly the PAO membrane fuses with the spinal dura rather than the atlas; and (4) the nuchal ligament does not exist in the PAO interspace.

Conclusions: The connective tissue structures that connect the spinal dura to the RCPm muscle in the PAO interspace are the RCPm fascia and tendinous fibers and perivascular sheathes.

Investigation of meningomyovertebral structures within the upper cervical epidural space: a sheet plastination study with clinical implications.

Spine J. 2015 Nov 1;15(11):2417-24. Frank Scali, Matthew E Pontell, Lance G Nash, Dennis E Enix.

Background context: Over the past two decades, soft-tissue structures communicating with the dura mater within the epidural space have become the focus of many anatomical and histopathologic studies. The relationship between these bridging structures has yet to be evaluated in situ.

Purpose: This is the first study that used E12 sheet plastination to investigate the epidural space of the upper cervical spine in situ and its associated bridging structures. Given the complexity of this space, this study may prove useful to clinical anatomists and surgeons who operate within this region.

Study design: Anatomical and microscopic analyses of structures that communicate with the dura mater within the upper cervical region were carried out.

Methods: Gross dissection in conjunction with microscopy was used to evaluate bridging communications of the upper cervical spine in 10 cadavers. To evaluate the in situ arrangement of these structures, E12 sheet plastination was used on 13 cadavers.

Results: In all 23 specimens, suboccipital fascia coalesced with the dorsal meningovertebral ligament of the atlas, and inserted directly into the posterior surface of the dura as a single but separable laminar layer. At the level of the atlantoaxial interspace, suboccipital fasciae combined and coalesced with the dorsal meningovertebral ligament of the atlas and the axis. These structures inserted into the posterior surface of the dura mater as a single but separable layer. Microscopy validated these findings and E12 sheet plastination revealed the in situ organization of these soft-tissue structures. E12 sheet plastination also provided new information on dural arrangement at the craniocervical junction, which was observed to be composed of periosteum from the occiput but consisted mainly of deep fascia from the rectus capitis posterior minor.

Conclusions: E12 sheet plastination has provided in situ visualization of bridging structures within the cervical epidural space and offers new insight into these structures, as well as the composition and arrangement of the posterior atlantooccipital membrane and cerebrospinal dura at the craniocervical junction. This study aims to expand on the anatomical understanding of the upper cervical region while defining structures that may reduce neurosurgical complications, and aid in the understanding of the pathophysiology of certain neurogenic disorders.

Dentate ligament: cord distortion hypothesis.

Chiropr Res J. 1988;1(1):47–55. J. Grostic.

The Dentate Ligament – Cord Distortion Hypothesis, utilizes the unique anatomy of the cervical spine to provide a model which explains how a misalignment of C-1 or C-2 can produce neurological insult directly via mechanical irritation of the spinal cord, and indirectly via vascular compromise of the cervical cord. This hypothesis states that misalignments of the upper cervical vertebrae, because of their unique attachments to the spinal cord by means of dentate ligaments, can directly stress and deform the spinal cord.

The Posterior Atlantooccipital Membrane: The Anchor for the Myodural Bridge and Meningovertebral Structures.

Cureus. 2022 May 30;14(5):e25484. Frank Scali, Ai Ohno, Dennis Enix, Sherif Hassan.

Introduction: Sheet plastination has provided evidence that the posterior atlantooccipital membrane attaches to the dura's posterior sleeve at the cerebrospinal junction. These findings contradict the traditional anatomical description of this membrane extending from the atlas' posterior arch to the foramen magnum.

Methods: A total of 16 plastinated cadavers were studied to evaluate the in situ and gross configuration of the posterior atlantooccipital membrane. Fifteen cadavers underwent sheet plastination, and one head was hemisected and plastinated. In all specimens, stereomicroscopy was used to evaluate the posterior atlantooccipital membrane and related structures within the intervertebral and epidural spaces.

Results: In all 16 specimens, the posterior atlantooccipital membrane extending from the occiput, merged with the craniocervical dura mater, and formed a membrane-dura complex that ended at the level of the third cervical vertebra. The superior and inferior myodural bridge coalesced with their respective vertebroductal ligaments and fused with the posterior atlantooccipital membrane at their respective interspaces.

Conclusion: The median aspect of the posterior atlantooccipital membrane does not directly communicate with the posterior arch of the atlas. Instead, the posterior atlantooccipital membrane converges with the craniocervical dura mater and terminates at the level of the third cervical vertebra. This membrane-dura complex serves as a common attachment site for the myodural and vertebroductal structures.

Connection between the spinal dura mater and suboccipital musculature: evidence for the myodural bridge and a route for its dissection – a review.

Clin Anat. 2012 May;25(4):415-22. Kourosh Kahkeshani, Peter J Ward.

A connective tissue link between the spinal dura mater and the rectus capitis posterior minor muscle was first described in 1995 and has since been readily demonstrated via dissection, magnetic resonance imaging, and plastinated cross-sections of the upper cervical region (Hack et al. [1995] Spine 20:2484-2486). This structure, the so-called "myodural bridge," has yet to be included in any of the American anatomy textbooks or dissection guides commonly used in medical education. This direct anatomic link between the musculoskeletal system and the dura mater has important ramifications for the treatment of chronic cervicogenic headache. This article summarizes the anatomic and clinical research literature related to this structure and provides a simple approach to dissect the myodural bridge and its attachment to the posterior atlanto-occipital membrane/spinal dura mater complex and summarizes the case for its possible inclusion in medical anatomy curricula.

Utilization of MR imaging in myodural bridge complex with relevant muscles: current status and future perspectives.

J Musculoskelet Neuronal Interact. 2020 Sep 1;20(3):382-389. Mei-Yu Sun, Hong-Jin Sui, Khalid Eteer, Sheng-Bo Yu, Jia-Ni Hu.

The aim of this study is to review and discuss the literature on the utilization of magnetic resonance imaging (MRI) in investigating the structure and feasible function of the myodural bridge complex (MDBC) with relevant muscles, which will be useful to understand the function of the MDB. The myodural bridge (MDB) is a soft tissue connective bridge that provides a fascial continuity between the musculature/ligament and cervical spinal dura mater (SDM) in the suboccipital areas. All of these involved structures are referred to as the MDBC. It would transfer tensile forces effectively from involved suboccipital muscles/ligament to SDM during head movement. Despite present achievements, its anatomic and functional role is still unclear. MRI enables not only in vivo visualization of ligaments, musculature and spinal dura with conventional T1W, T2W and PDW imaging, but also functional evaluation of MDBC with relevant muscles, such as muscles' fatty infiltration, cross-sectional area changes and injuries. Though some functional MRI techniques have not been used for the MDBC with relevant muscles now, these techniques have great potential to better understand function of MDBC including its suspected clinical role. MRI is likely the most powerful tool to study MDBC and relevant muscles with only limited exploration so far.

A proposed etiology of cervicogenic headache: the neurophysiologic basis and anatomic relationship between the dura mater and the rectus posterior capitis minor muscle.

J Manipulative Physiol Ther. 1999 Oct;22(8):534-9. M E Alix, D K Bates.

Objective: To examine the neurophysiologic basis and anatomic relationship between the dura mater and the rectus capitis posterior minor muscle in the etiologic proposition of cervicogenic headache.

Data sources: On-line searches in MEDLINE and the Index to Chiropractic Literature, manual citation searches, and peer inquiries.

Results: Connective tissue bridges were noted at the atlanto-occipital junction between the rectus capitis posterior minor muscle and the dorsal spinal dura. The perpendicular arrangement of these fibers appears to restrict dural movement toward the spinal cord. The ligamentum nuchae was found to be continuous with the posterior cervical spinal dura and the lateral portion of the occipital bone. Anatomic structures innervated by cervical nerves C1-C3 have the potential to cause headache pain. Included are the joint complexes of the upper 3 cervical segments, the dura mater, and spinal cord.

Conclusion: A sizable body of clinical studies note the effect of manipulation on headache. These results support its effectiveness. The dura-muscular, dura-ligamentous connections in the upper cervical spine and occipital areas may provide anatomic and physiologic answers to the cause of the cervicogenic headache. This proposal would further explain manipulation's efficacy in the treatment of cervicogenic headache. Further studies in this area are warranted to better define the mechanisms of this anatomic relationship.

The obliquus capitis inferior myodural bridge.

Clin Anat. 2013 May;26(4):450-4. Matthew E Pontell, Frank Scali, Eward Marshall, Dennis Enix.

This study was designed to examine the obliquus capitis inferior (OCI) muscle from a gross anatomical perspective. The objective was to isolate and identify the OCI myodural bridge, while examining its course and contributing elements. An earlier study of the posterior cervical spine briefly reported a connection between the OCI and the cervical dura mater. To the best of our knowledge, a study has not yet been conducted specifically on this muscle and its relation to the dura mater. In this study, the suboccipital regions of nine embalmed cadavers were dissected. A total of 14 OCI muscles were isolated for examination. All findings were documented via photograph. Of the 14 OCI muscles isolated, all emitted fibrous tissue bands from the anterolateral portion of the muscular belly. These fibers attached to the posterolateral cervical dura mater by route of the atlantoaxial interspace. The OCI myodural bridge appeared to coalesce with the rectus capitis posterior major myodural bridge, giving the appearance of a single atlantoaxial structure that links these two muscles to the dura mater. In conclusion, the OCI was attached to the dura mater in all of the 14 muscle specimens. We hypothesize that the OCI myodural bridge may play a physiological role in monitoring dural tension and preventing dural infolding. It may also contribute to certain clinical symptoms manifesting from alterations in dural tone.

A Systematic Review of the Soft-Tissue Connections Between Neck Muscles and Dura Mater: The Myodural Bridge.

Spine (Phila Pa 1976). 2017 Jan 1;42(1):49-54. Luis Palomeque-Del-Cerro, Luis A Arráez-Aybar, Cleofás Rodríguez-Blanco, Rafael Guzmán-García, Mar Menendez-Aparicio, Ángel Oliva-Pascual-Vaca.

Study design: Systematic review.

Objective: To elucidate the existence of soft tissue connections between the neck muscles and cervical dura mater.

Summary of background data: Several studies discuss the existence of a cervical myodural bridge; however, conflicting data have been reported.

Methods: Searches were conducted in the PubMed, Web of Science, Cochrane Library, and PEDro databases. Studies reporting original data regarding the continuity of non-post-surgical soft tissue between the cervical muscles and dura mater were reviewed. Two reviewers independently selected articles, and a third one resolved disagreements. Another two researchers extracted the methodology of the study, the anatomical findings, and evaluated the quality of the studies using Quality Appraisal for Cadaveric Studies Scale. A different third researcher resolved disagreements.

Results: Twenty-six studies were included. A soft tissue connection between the rectus capitis posterior minor, the rectus capitis posterior major, and the obliquus capitis inferior muscles seems to be proved with a strong level of evidence for each one of them. Controversy exists about the possible communication between the dura mater and the upper trapezius, rhomboideus minor, serratus posterior superior, and splenius capitis by means of the ligamentum nuchae. Finally, there is limited evidence about the existence of a soft tissue connection between rectus capitis anterior muscle and the dura mater.

Conclusion: There is a continuity of soft tissue between the cervical musculature and the cervical dura mater; this might have physiological, pathophysiological, and therapeutic implications, and going some way to explaining the effect of some therapies in craniocervical disorders.

Rectus Capitis Posterior Minor: Histological and Biomechanical Links to the Spinal Dura Mater.

Spine (Phila Pa 1976). 2017 Apr 15;42(8):E466-E473. Gabriel Venne, Brian J Rasquinha, Manuela Kunz, Randy E Ellis.

Study design: Serial histological investigation was performed on 10 cadaveric specimens and biomechanical tests were performed on five specimens, both focused on the tissue connexion between the rectus capitis posterior minor (RCPMi) and the spinal dura.

Objective: This study had two components: to clarify the microscopic structure of the tissue link between RCPMi and the dura mater, and to evaluate the mechanical role of this tissue complex.

Summary of background data: Dissection-based and imaging-based reports have suggested a connective tissue link between the RCPMi and the dura mater at the posterior-atlanto-occipital (PAO) level. Existence of this link, and properties, remain unclear.

Methods: Histological investigation: RCPMi muscles, their bony attachments, PAO space, and adjacent spinal dura mater were resected from 10 cadavers. Tissues were subdivided into medial and lateral parts. Serial histological sections were prepared to cover maximum surface area; Masson trichrome stain was used to evaluate the tissue connection. Biomechanical investigation: individualized RCPMi muscles from five cadavers were detached from their origin. Each muscle was loaded incrementally up to 2 kg, with the cervical spine hyperextended. Using a structured light scanner, the dura mater was scanned for each loaded state. Comparison between unloaded and each loaded scanned surface quantified the displacement of the dura mater.

Results: Histological investigation confirmed the existence of a connective tissue link between the RCPMi and the dura mater. The biomechanical testing suggests that this tissue link complex can reduce the bulging of the dura mater into the spinal canal, caused during hyperextension, by $53.4\% \pm 6.9\%$ under RCPMi loading.

Conclusion: This histological investigation clarified the structure of the tissue link between the RCPMi and the dura mater. The biomechanical testing indicated a potential mechanical function of the RCPMi in regards to the spinal dura mater, which may include a stabilizing role of the dura mater during neck extension.

Investigation of connective tissue attachments to the cervical spinal dura mater.

Clin Anat. 2003 Mar;16(2):152-9. B K Humphreys, Shahar Kenin, Bradley B Hubbard, Gregory D Cramer.

The connective tissue attachments to the cervical spinal dura mater originating from the ligamentum nuchae (LN) and rectus capitis posterior minor (RCPM) muscle were evaluated in 30 cadaveric spines. Magnetic resonance images (MRIs) were correlated with the attachments in four cadaveric specimens. Attachments from the LN to the RCPM were also identified. The LN and the RCPM to dura attachments were found in all 30 specimens. Our results indicate that: 1) the attachments between the LN and RCPM and the dura occur between vertebrae C1-C2 and the occipital bone and C1, respectively, and that they are substantial normal anatomic attachments, 2) attachments between the LN and RCPM are usually present, and 3) the attachments between the LN and dura mater can be identified on MRI. These latter attachments may play a role in neck pain, making their MRI appearance clinically important.

Orientation and property of fibers of the myodural bridge in humans.

Spine J. 2018 Jun;18(6):1081-1087. Nan Zheng, Yan-Yan Chi, Xiao-Han Yang, Nan-Xing Wang, Yi-Lin Li, Yang-Yang Ge, Lan-Xin Zhang, Tai-Yuan Liu, Xiao-Ying Yuan, Sheng-Bo Yu, Hong-Jin Sui.

Background context: Studies over the past 20 years have revealed that there are fibrous connective tissues between the suboccipital muscles, nuchal ligament, and cervical spinal dura mater (SDM). This fibrous connection with the SDM is through the posterior atlanto-occipital or atlantoaxial interspaces and is called the myodural bridge (MDB). Researchers have inferred that the MDB might have important functions. It was speculated that the function of MDB might be related to proprioception transmission, keeping the subarachnoid space and the cerebellomedullary cistern unobstructed, and affecting the dynamic circulation of the cerebrospinal fluid. In addition, clinicians have found that the pathologic change of the MDB might cause cervicogenic or chronic tension-type headache. Previous gross anatomical and histologic studies only confirmed the existence of the MDB but did not reveal the fiber properties of the MDB. This is important to further mechanical and functional research on the MDB.

Purpose: Multiple histologic staining methods were used in the present study to reveal the various origin and fiber properties of the MDB. Muscles and ligaments participating in forming the MDB at the posterior atlanto-occipital or atlantoaxial interspaces were observed, and the fiber properties of the MDB were confirmed. The present study provides a basis for speculating the tensile force values of the MDB on the SDM and a morphologic foundational work for exploring the physiological functions and clinical significances of the MDB.

Study design: Anatomical and histologic analyses of suboccipital structures that communicate with the SDM at the posterior atlanto-occipital or atlantoaxial interspaces were carried out.

Methods: Multiple histologic staining methods were used to evaluate the histologic properties and composition of the MDB at the posterior atlanto-occipital or atlantoaxial interspaces in five formalin-fixed head-neck human specimens.

Results: The results show that the MDB traversing the atlanto-occipital interspace originated from the rectus capitis posterior minor (RCPmi). The MDB traversing the atlantoaxial interspace originated mainly from the RCPmi, rectus capitis posterior major, and obliquus capitis inferior. These fibers form the vertebral dural ligament in the atlantoaxial interspace and connect with SDM. The MDB is mainly formed by parallel running type I collagen fibers; thus, suboccipital muscle could pull SDM strongly through the effective force propagated by the MDB during head movement.

Conclusions: Myodural bridge is mainly formed by parallel running type I collagen fibers; thus, it can transmit the strong pull from the diverse suboccipital muscles or ligaments during head movement. The results of the present study will serve as a basis for further biomechanical and functional MDB research.

Histological analysis of the rectus capitis posterior major's myodural bridge.

Spine J. 2013 May;13(5):558-63. Frank Scali, Matthew E Pontell, Dennis E Enix, Eward Marshall.

Background context: In recent literature, a soft-tissue communication between the rectus capitis posterior major (RCPma) muscle and the cervical dura mater has been identified. To the best of our knowledge, this communication has yet to be validated from a histological perspective nor has it been examined for neural tissue.

Purpose: The purpose of this study was to examine the composition and true continuity of the communication between the RCPma and the dura mater at a microscopic level. The communication was also inspected for the presence of proprioceptive neurons.

Study design: An anatomical and histological analysis of a novel structure in the atlantoaxial interspace.

Methods: Gross dissection was performed on 11 cadavers to remove the RCPma, the soft-tissue communication, and a section of posterior cervical dura mater as one continuous unit. Paraffin embedding and sectioning followed by hematoxylin and eosin staining was conducted to validate the connection. Staining with antineurofilament protein fluorescent antibodies was performed to identify proprioceptive neural tissue on one specimen, and all findings were recorded via photographic documentation.

Results: Histological investigation revealed a tendinous matrix inserting into both the RCPma and the posterior aspect of the cervical dura mater in all 11 specimens. In the one specimen examined for neural tissue, antineurofilament protein fluorescence revealed proprioceptive neurons within the communication. Immunoperoxidase staining demonstrated the insertion of these neurons into both the dura mater and the belly of the RCPma.

Conclusions: The existence of a true connection between the RCPma and the cervical dura mater provides new insight in understanding the complex anatomy of the atlantoaxial interspace. The presence of a neural component within this connection suggests that it may serve another function aside from simply anchoring this muscle to the dura mater. Such a connection may be involved in monitoring dural tension and may also play a role in certain cervicogenic pathologies. This study also supports previous reports that no true membrane joins the posterior arch of the atlas to the laminae of the axis and contradicts the conventional belief that the ligamentum flavum joins these two structures.

Anatomy and clinical relevance of sub occipital soft tissue connections with the dura mater in the upper cervical spine.

PeerJ. 2020 Aug 10;8:e9716. Rob Sillevs, Russell Hogg.

Background: The upper cervical region is a complex anatomical structure. Myodural bridges between posterior suboccipital muscles and the dura might be important explaining conditions associated with the upper cervical spine dysfunction such as cervicogenic headache. This cadaver study explored the upper cervical spine and evaluated the myodural bridges along with position of spinal cord in response to passive motion of upper cervical spine.

Methods: A total of seven adult cadavers were used in this exploratory study. The suboccipital muscles and nuchal ligament were exposed. Connections between the Rectus Capitis Posterior major/minor and the Obliquus Capitis minor, the nuchal ligament, posterior aspect of the cervical spine, flavum ligament and the dura were explored and confirmed with histology. The position of the spinal cord was evaluated with passive motions of the upper cervical spine.

Outcomes: In all cadavers connective tissues attaching the Rectus Capitis Posterior Major to the posterior atlanto-occipital membrane were identified. In the sagittal dissection we observed connection between the nuchal ligament and the dura. Histology revealed that the connection is collagenous in nature. The spinal cord moves within the spinal canal during passive movement.

Discussion: The presence of tissue connections between ligament, bone and muscles in the suboccipital region was confirmed. The nuchal ligament was continuous with the meniovertebral ligament and the dura. Passive upper cervical motion results in spinal cord motion within the canal and possible tensioning of nerve and ligamentous connections.

Anatomic relation between the rectus capitis posterior minor muscle and the dura mater.

Spine (Phila Pa 1976). 1995 Dec 1;20(23):2484-6. G D Hack, R T Koritzer, W L Robinson, R C Hallgren, P E Greenman.

Study design: Anatomic study of the suboccipital region, specifically the deep muscles of the suboccipital triangle, was performed in cadaveric specimens.

Objective: To observe and describe the relationship between the deep suboccipital musculature and the spinal dura.

Summary of background data: A review of the literature revealed no reports describing a physical connection between suboccipital musculature and the spinal dura.

Methods: Dissections of the suboccipital region were performed in 10 embalmed and one fresh sagittally hemisected head and neck specimens.

Results: A connective tissue bridge between the rectus capitis posterior minor muscle and the dorsal spinal dura at the atlanto-occipital junction was observed in every specimen. The fibers of the connective tissue bridge were oriented primarily perpendicular to the dura. This arrangement of fibers appears to resist movement of the dura toward the spinal cord.

Conclusions: Awareness of the physical relation between the rectus capitis posterior minor muscle and spinal dura via this connective tissue bridge should lessen the potential risk of dural damage during surgery. **This connective tissue bridge may help resist dural infolding during head and neck extension.**

The morphology and clinical significance of the dorsal meningovertebra ligaments in the cervical epidural space.

Spine J. 2014 Nov 1;14(11):2733-9. Benchao Shi, Xuefeng Zheng, Shaoxiong Min, Zhilai Zhou, Zihai Ding, Anmin Jin.

Background context: The dural sac is anchored within the vertebral canal by connective tissue called meningovertbral ligaments in the epidural space. During flavectomy and laminectomy, inadvertent disruption of the dorsal meningovertbral ligaments may lead to dura laceration and cerebrospinal fluid (CSF) leaks. All the described dorsal meningovertbral ligaments were located in the lumbar region. A rare study is available about dorsal meningovertbral ligaments of the cervical spinal dura to the adjacent vertebrae.

Purpose: To identify and describe the dorsal meningovertbral ligaments at each cervical level and discuss their clinical significance.

Study design: A dissection-based study of 22 embalmed cadavers.

Methods: The anatomy was studied in 22 whole cervical cadavers (11 females, 11 males), prepared with formaldehyde, whose ages at the time of death ranged from 55 to 78 years. The vertebral canal was divided to expose the dural sac and the spinal nerve roots. At all levels of the cervical vertebra, the morphology, quantity, origin, insertion, and spatial orientation of the dorsal meningovertbral ligaments were determined and the length, width or diameter, and thickness of the ligaments were measured with vernier calipers.

Results: **The dorsal meningovertbral ligaments in the cervical region anchored the posterior dural sac to the ligamentum flavum or laminae.** The number of attachment points on the ligamentum flavum was relatively larger than that on the lamina, and **the occurrence rate of dorsal meningovertbral ligaments was 100% at C1-C2 and C4-C5. The thickest ligaments were observed at the C1 and C2 vertebrae.** The length of the ligaments varied from 1.50 to 35.22 mm, and the orientation of the ligaments mostly was craniocaudal. The morphology of the dorsal meningovertbral ligaments was divided into four types: strip type, cord type, grid type, and thin slice type.

Conclusions: In the cervical spine, the dorsal meningovertbral ligaments exist between the posterior dural sac and the ligamentum flavum or lamina. The dorsal meningovertbral ligaments may be of clinical importance to surgeons. Dissecting the dorsal meningovertbral ligaments before the cervical flavectomy and laminectomy may be an important step in reducing postoperative dura laceration and CSF leaks, which may result in significant benefits for patients and health-care organizations.

The anatomic relation among the nerve roots, intervertebral foramina, and intervertebral discs of the cervical spine.

Spine (Phila Pa 1976). 2000 Feb 1;25(3):286-91. N Tanaka, Y Fujimoto, H S An, Y Ikuta, M Yasuda

Study design: An anatomic study of the cervical intervertebral foramina, nerve roots, and intradural rootlets performed using a surgical microscope.

Objectives: To investigate the anatomy of cervical root compression, and to obtain the anatomic findings related to cervical foraminotomy for the treatment of cervical radiculopathy.

Summary of background data: Cervical foraminotomy is a procedure performed frequently for the management of cervical radiculopathy. However, anatomic studies of cervical foraminotomy have not been fully elucidated.

Methods: In this study, 18 cadavers were obtained for the study of the cervical spine. All the soft tissues were dissected from the cervical spine. Thereafter, laminectomy and facetectomy were performed on C4 through T1 using a surgical microscope. The nerve roots and surrounding anatomic structures, including intervertebral discs and foramina, were exposed. In addition, the intradural rootlets and their intersegmental connections were observed.

Results: The shape of the intervertebral foramina approximated a funnel, the entrance zone being the most narrow part and the root sleeves conical, with their takeoff points from the central dural sac being the largest part. Therefore, compression of the nerve roots occurred at the entrance zone of the intervertebral foramina. Anteriorly, compression of the nerve roots was caused by protruding discs and osteophytes of the uncovertebral region, whereas the superior articular process, the ligamentum flavum, and the periradicular fibrous tissues affected the nerve posteriorly. The C5 nerve roots were found to exit over the middle aspect of the intervertebral disc, whereas the C6 and C7 nerve roots were found to traverse the proximal part of the disc. The C8 nerve roots had little overlap with the C7-T1 disc in the intervertebral foramen. **The C6 and C7 rootlets passed two disc levels in the dural sac. Also, a high incidence of the intradural connections between the dorsal rootlets of C5, C6, and C7 segments was found.**

Conclusions: This study demonstrated the anatomy of the nerve roots, rootlets, and intervertebral foramina, and may aid in understanding the pathology of cervical radiculopathy. The presence of intradural connections between dorsal nerve roots and the relation between the course of the nerve root and the intervertebral disc may explain the clinical variation of symptoms resulting from-nerve root compression in the cervical spine. To perform cervical foraminotomy for cervical radiculopathy, it is necessary to understand the detailed anatomy of the intervertebral foramina thoroughly.

Neural tension patterns during cervical spine rotation: diagnostic implications from a cadaveric study.

Background: Cervical neural tension reflects the biomechanical and physiological responses of spinal nerves to positional changes. Although clinical tests exist for the lower cervical spinal nerve, tension patterns in the upper and mid-cervical nerves remain underexplored, limiting the diagnostic accuracy for conditions such as occipital neuralgia.

Methods: This cadaveric study quantified tensile load changes at the cervical spinal nerve level (C1-C5) during passive cervical spine rotation in five formalin-embalmed cadavers. Tension was measured on the cervical spinal nerves (C1-C5) using force gauges attached proximal to the division between the dorsal and ventral rami. C1 measurements were obtained from a single specimen. Two movement conditions were used: cervical flexion-rotation for C1-C3 and neutral-plane rotation for C4-C5.

Results: Ipsilateral increases in neural tension were observed in C1-C3 during flexion-rotation movements. By contrast, C4-C5 exhibited a consistent pattern of contralateral load increase during rotation in the neutral plane. Statistically significant variations in the tensile load were observed at the C5 level under different rotation conditions, specifically at C5 left ($p = 0.003$) and C5 right ($p = 0.006$). Post-hoc analyses of C5 measurements during neutral-plane rotation revealed significant differences between right and left rotation ($p = 0.018$) and between left rotation and neutral rotation ($p = 0.018$) on the left side, as well as between right rotation and left rotation and neutral rotation ($p = 0.026$, $p = 0.024$) on the right side. Intraclass correlation coefficients (ICC) indicated good-to-excellent reliability (ICC > 0.75), particularly at C2-C5.

Conclusions: Cervical rotation influenced neural tension, with distinct patterns observed between the upper cervical segments (tested under flexion-rotation) and the middle cervical segments (tested under neutral plane rotation). These exploratory findings suggest that replacing lateral neck flexion with rotation in the upper-limb tension test may represent a promising direction for future research. Additionally, the flexion-rotation test may provide a basis for clinical validation as a potential indicator of greater occipital nerve tension. These results lay the groundwork for refining neurodynamic assessments and warrant further in vivo investigation.

Anatomic study and clinical significance of the dorsal meningovertebral ligaments of the thoracic dura mater.

Spine (Phila Pa 1976). 2015 May 15;40(10):692-8. Rongzi Chen, Benchao Shi, Xuefeng Zheng, Zhilai Zhou, Anmin Jin, Zihai Ding, Hai Lv, Hui Zhang.

Study design: A dissection-based study of 18 embalmed thoracic specimens.

Objective: To investigate the properties and clinical significance of the dorsal meningovertebral ligaments of the thoracic dura mater.

Summary of background data: Previously, we performed a comprehensive anatomic study on the dorsal meningovertebral ligaments in the lumbosacral and cervical regions, whereby we concluded that the ligaments were an anatomic factor leading to dural laceration and hemorrhage during flavectomy and laminectomy. Unfortunately, thus far, no systematic anatomic study has been undertaken to examine the dorsal meningovertebral ligaments of the thoracic dura mater.

Methods: Eighteen adult embalmed cadavers were studied, and the morphology, orientation, attachment site, and distribution traits of the dorsal meningovertebral ligaments were observed. In addition, the length, width, or diameter and thickness of the ligaments were measured using a Vernier caliper. Two meningovertebral ligaments were removed for histological examination.

Results: In the thoracic region, the dorsal meningovertebral ligaments anchored the dura mater to the lamina or ligamentum flavum. The meningovertebral ligaments displayed a relatively even distribution along the upper thoracic region (T1-T7) and a gradual increase in frequency in the lower thoracic region from T7 to T12. The meningovertebral ligaments protrude into the dura and correspondingly become an integral part of the dura. Some ligaments are accompanied by or are attached to blood vessels. Histological examination of the meningovertebral ligaments revealed fibrous connective tissue.

Conclusion: The dorsal meningovertebral ligaments exist between the dural sac and ligamentum flavum or lamina in the thoracic spine. Based on their anatomic features, meningovertebral ligaments may be one potential cause for dural laceration and epidural hemorrhage. We propose that, during thoracic flavectomy and laminectomy, the meningovertebral ligaments should first be identified and properly handled, thereby minimizing the occurrence of relevant complications.

The anterior dural (Hofmann) ligaments.

Spine (Phila Pa 1976). 2004 Mar 15;29(6):623-7. Sharan Wadhwani, Peter Loughenbury, Roger Soames.

Study design: A dissection-based study of 18 embalmed cadavers (7 male, 11 female), mean age 84 (+/-8.4) years.

Objective: To determine the morphology and morphometry of the anterior dural (Hofmann) ligaments.

Summary of background data: The attachment of the posterior longitudinal ligament to the dura mater is poorly understood. Anterior dural ligaments connect the anterior dura to the deep layer of the posterior longitudinal ligament, but appear to be limited to the lumbar region and have been observed to have a craniocaudal orientation. Their function is reported to help in supporting and protecting the dural sac and spinal cord.

Methods: The spinal canal was opened exposing the dural sac, the spinal nerve roots incised, and spinal cord removed to mobilize the dural sac and gain access to Hofmann ligaments. The extent, orientation, length, and level of origin and insertion of the ligaments were documented.

Results: The orientation of the ligaments changed from caudocranial (dura to posterior longitudinal ligament) at upper thoracic levels to transverse at the level of T8-T9 to craniocaudal at lower thoracic and lumbar levels, often with multiple ligaments being present at a single level. Ligament length varied from 0.5 to 28.8 mm and was positively correlated with vertebral level and negatively correlated with orientation.

Conclusions: Hofmann ligaments are present at most levels between C7 and L5; although most ligaments were limited to a single vertebral segment, some were observed to cross several segments.

Biomechanics of the lumbar spinal canal.

Clin Biomech (Bristol). 1986 Feb;1(1):31-43. J D Troup.

The normal mobility of the vertebral column, particularly in the cervical and lumbar regions, gives rise to major changes in the length and lumen of the spinal canal and of its volume. Its contents must therefore adapt to these changes without disturbance to their several functions. The contents are partly fluid, partly neural tissue, but also connective tissue: all with differing physical characteristics. Thus, all respond differently to changes in the space in which they are contained. When pathological changes supervene, the spinal meninges, the spinal cord and nerve roots may be adversely affected by the increases in the resting tension, by compression or bending stresses. Because the mechanical state of one region of the spine has a more than local effect, all these factors have to be considered- particularly for the interpretation of the symptoms and clinical signs of lumbosacral root pathology.

Intrathecal ligaments and nerve root tension: possible sources of lumbar pain during spaceflight.

Aviat Space Environ Med. 2004 Apr;75(4):354-8. David Kershner, Robert Binhammer.

Lumbar intrathecal ligaments have recently been demonstrated to randomly bind dorsal nerve roots to the dura within the lumbar vertebral column. Lengthening of the vertebral column and associated lumbar back pain experienced by astronauts is common in microgravity. This study was designed to investigate the relationship of lumbar intrathecal ligaments in spinal lengthening as a possible mechanism for back pain.

Methods: A two-part study was designed using 36 vertebral columns from embalmed cadavers. There were 12 vertebral columns studied in mid-sagittal section to demonstrate the possible movement of the spinal cord during lengthening of the vertebral column. The remainder were assessed for the amount of tension placed on a dorsal nerve root by the lumbar intrathecal ligament during lengthening of the vertebral column.

Results: The spinal cord moves in a cephalic direction approximately 2.8 mm with 4 cm lengthening of the vertebral column. During lengthening, a loss of thoracic and lordotic curvature was noted with an increase in disk height. Tension was significantly increased on the dorsal nerve roots being tethered by the lumbar intrathecal ligaments in comparison to non-tethered nerve roots during lengthening of the vertebral column.

Conclusion: A significant amount of tension is placed on dorsal nerve roots tethered by intrathecal ligaments within the lumbar spine during spinal lengthening. These ligaments randomly bind dorsal nerve roots in the lumbar spine and may be involved in the back pain experienced by astronauts in microgravity.

Meningovertebral ligaments and their putative significance in low back pain.

J Manipulative Physiol Ther. 1996 Nov-Dec;19(9):592-6. S D Bashline, J R Bilott, J P Ellis.

Objective: To determine the presence and morphology of the meningovertebral ligaments (ligaments of Hofmann) as well as postulate their possible contribution to low back pain.

Design: Sagittal dissections were performed on 12 embalmed cadaver specimens including the L5/S1 intervertebral level cephalad to T1. Meningovertebral ligaments were labeled and documented in both the lumbar and thoracic regions.

Results: Meningovertebral ligaments were found in both the lumbar and thoracic regions of all cadaveric specimens. These ligaments were much more prevalent in the lumbar vertebral column but were also present throughout the thoracic vertebral column. The meningovertebral ligaments in the lumbar region were more robust as well as more frequently encountered than those found in the thoracic region.

Conclusion: Dural sac attachments to the posterior aspect of the vertebral bodies and the posterior longitudinal ligament could act to traction the dural sac in the event of nuclear bulge or herniation. The prevalence of these ligaments in the lumbar spine, coupled with the high incidence of herniated nucleus pulposus and disc bulges in this region, may compound the effects of disc pathology and result in increased low back pain.

Lumbar intrathecal ligaments.

Clin Anat. 2002 Mar;15(2):82-7. David E Kershner, Robert T Binhammer

A meticulous examination was performed on 56 vertebral columns from cadavers between 64 and 89 years of age. Identification of all contents within the dural sac was completed; however, the main focus was the cauda equina and lumbar region. In addition to scope dissection, radiographs and histological preparations were used to identify

structures, tissue types, and any possible pathology. Discrete intrathecal ligamentous bands were observed in all cadavers examined. They were found randomly binding the dorsal nerve roots of the cauda equina to the dura. Occasional binding of the ventral nerve roots to the dorsal roots was observed. Histological examination demonstrated a dense collagen ligament varying between 0.13 and 0.35 microm in thickness and from 3 mm to 3.5 cm in length. The average number of ligaments found per cadaver was 18. These ligaments displayed a broad base attachment to the nerve root or dura of approximately 3 mm. Looping of the nerve roots associated with these ligaments was seen in one cadaver with a burst fracture. Electron microscopic studies of these ligaments demonstrated similarities to denticulate ligaments. It is suggested that the intrathecal ligaments represent remnants from fetal development of the denticulate ligaments.

The morphology and clinical significance of the dorsal meningovertebra ligaments in the lumbosacral epidural space.

Spine (Phila Pa 1976). 2012 Aug 15;37(18):E1093-8. Benchao Shi, Xiangming Li, Hongliang Li, Zihai Ding

Study design: A dissection-based study of 30 embalmed cadavers.

Objective: To determine the morphology and morphometry of the dorsal meningovertbral ligaments in the lumbosacral segments and to discuss their clinical significance.

Summary of background data: Postoperative cerebrospinal fluid leakage is associated with longer hospital stays and significant implications for the patient, the surgeons, and society as a whole. To protect the dural sac during lumbar surgery, knowledge of the surgical anatomy of the dorsal meningovertbral ligaments is crucial.

Methods: A total of 30 adult embalmed cadavers (52-70 yr of age; mean age of 64 yr) were used. The vertebral canal was divided to expose the dural sac and the spinal nerve roots, and the spinal cord was removed. The morphology, quantity, and attachment of the dorsal meningovertbral ligaments in the lumbosacral region were observed, and the length, width, or diameter and thickness of the ligaments were measured with vernier calipers.

Results: The dorsal meningovertbral ligaments in the lumbosacral region connect the dura to the ligamenta flava or the lamina. The number of the attachment points on the ligamenta flava was relatively larger than that on the lamina, and the occurrence rate of dorsal meningovertbral ligaments was 97% at L5-S1. The thickest ligaments were observed at the L5 and S1 vertebrae. The length of the ligaments varied from 5.16 to 40.24 mm, and the ligaments extended caudally from their origin on the dura to their attachment to the lamina or the ligamentum flavum. The morphology of the dorsal meningovertbral ligaments was divided into 5 types: strip type, cord type, "Y"-shaped type, grid type, and thin slice type.

Conclusion: The dorsal meningovertbral ligaments may contribute to dura laceration and epidural hemorrhage during flavectomy and laminectomy, and an appreciation of this relationship might help reduce the risk of such complications.

The ATA and its surgical importance: a newly described ligament lying between the dural sac and the ligamentum flavum at the L5 level.

Spine (Phila Pa 1976). 2011 Jul 15;36(16):1268-72. Ihsan Solaroglu, Ozerk Okutan, Ethem Beskonakli.

Study design: The anatomy of a new ligament in the human spine the ATA is described.

Objective: To describe a new ligament; the ATA, which lies between the dural sac and the ligamentum flavum at the L5 level and to discuss its surgical importance.

Summary of background data: Postoperative cerebrospinal fluid (CSF) leakage translates into longer hospital stays with significant implications for the patient, the health care system, and society as a whole. To avoid injury to the dural sac during lumbar surgery, it is crucial to know the surgical anatomy and its variations.

Methods: The length and the number of ATAs were examined in 14 consecutive patients, which underwent an L5 laminoflavectomy in our department. The ATA and its anatomic landmarks are described here for the first time in the literature. We named this ligament the ATA; reminding us to pay attention to the Terminal Attachment.

Results: The presence of the ATA is demonstrated in 10 patients (71%). There was a double ATA in four patients (40%). The mean length of the ATA was 7.7 ± 1.8 mm. The ATA originates from the dorsal surface of the dura mater at the level of the superior border of the superior facet of the S1 vertebra and projects toward the ligamentum flavum. Histologic examination of the ATA revealed fibrous connective tissue.

Conclusion: In this preliminary study, we have described a new ligament, the ATA, between the dural sac and the ligamentum flavum at the L5 level. The ATA is an important structure that creates a potential risk for inadvertent dural lacerations during flavectomy. Dissecting the ATA before the flavectomy may be an important step in reducing postoperative cerebrospinal fluid leaks, which may result in significant benefits for patients and health care organizations.

The posterior epidural ligaments: a cadaveric and histological investigation in the lumbar region.

ISRN Anat. 2013 Oct 2;2013:424058. M J Connor, S Nawaz, V Prasad, S Mahir, R Rattan, J Bernard, P J Adds.

Purpose: Incidental durotomy is a relatively common complication for patients undergoing posterior spinal surgery. Delineating anatomical variants in the posterior lumbar spinal canal is crucial in reducing future rates of incidental durotomy.

Materials and Methods: The ligamentous attachments between the dura mater and ligamentum flavum in the lumbar region of 17 soft-fixed cadavers were investigated. The lumbar vertebral columns were removed, and cross-sectional dissection was performed at levels L1-S1. Anterior retraction of the dorsal dura mater identified attachments between the dorsal surface of the dura mater and the ligamentum flavum. Histological staining of the ligamentous attachments was carried out with hematoxylin and eosin (H&E) and elastic van Gieson (EVG).

Results: Posterior epidural ligaments were present in 9 (52.9%) cadavers. Nine (9) separate ligaments were identified in these cadavers, with 3 (33.3%) at L3/L4, 5 (55.5%) at L4/L5, and 1 (11.1%) at L5/S1. Histology confirmed the presence of poorly differentiated collagen-based connective tissue, distinct from the normal anatomy.

Conclusions: This study confirms the presence of multiple dorsomedial posterior epidural ligaments at the main sites for posterior spinal surgery (L3-S1). An intraoperative awareness of the variability of such connections may be an important step in reducing static rates of incidental durotomy.

Meningeal-neural relations in the intervertebral foramen.

J Neurosurg. 1974 Jun;40(6):756-63. S Sunderland.

Anatomical background of low back pain: variability and degeneration of the lumbar spinal canal and intervertebral disc.

Schmerz. 2001 Dec;15(6):418-24. P van Roy, E Barbaix, J P Clarijs, S Mense.

The central and lateral lumbar canals constitute complex osteofibrous neurovascular tunnels, allowing movement and deformation of the spine without loss of their main configuration. Intervertebral discs play an important role in determining their configuration. Disc degeneration may alter or even threaten the functional anatomical relationships between successive adjacent "juncturae" of the vertebral column. Shape and morphometric aspects of the bony neural canals reveal level dependency, inter-individual variation, and are particularly susceptible for changes with aging. Articular tropism and other left-right differences may influence their morphology. In the epidural compartments behind the vertebral bodies, a sagittal membrane may totally or partly connect the deeper layer of the posterior longitudinal ligament (PLL) with the posterior midline of the vertebral body. This membrane is considered clinically significant in the prevention of movement of disc material from one side to the other at the level of the vertebral bodies. Meningovertebral ligaments represent a heterogeneous group of membranous formations, connecting the dura with the PPL and other elements of the spinal canal. They prevent the dura from moving away from the bony container. These ligaments may vary from loose areolar tissue to clearly individualised ligaments and from pure midsagittal septa to more laterally oriented attachments. A double cross vault structure between the PPL and the dura mater often extends from L3 to the end of the dural envelope. A retrospective study of medial and paramedial attachments in CT- and MRT-scans confirmed the presence of a mediosagittal structure below L3 in 35% of the cases. It was hypothesized that meningovertebral ligaments may play a role as a barrier to transverse displacement of extruded disc material. The surrounding morphology renders the lateral neural canal its typical inverted teardrop shape. The subpedicular notch of the upper vertebra provides the widest part and represents the neural foramen strictu sensu. The posterolateral aspect of two articulating vertebrae and the interposed intervertebral disc constitute the anterior wall. The morphology of the anteroinferior aspect of the intervertebral foramen strongly depends on the condition of the apophyseal rings and the intervertebral disc. The latter may show a slight physiological posterior bulging at lower lumbar levels. The posterior wall of the nerve root canal is represented by the ligamentum flavum, the pars interarticularis of the upper vertebra, and the superior articular facet of the vertebra below. Thickening of the ligamentum flavum must be considered in relationship to alterations of anterior components: trabecular reorganization and spreading of vertebrae in aging, and disc degeneration. Nerve root sleeves display a level dependent, variable oblique course from their emanation from the thecal sac towards the outer third of the neural canal. The presence of anomalous lumbosacral nerve roots may result in considerable course alterations, originating from an abnormal high or low level emanation, conjoined nerve roots, a double set of nerve roots or anastomosis between nerve roots of adjacent levels. Variation exists in the position of the dorsal root ganglia (DRG) relative to the intervertebral foramen. An intraforaminal position seems to be more common at L4 and L5 levels; an intraspinal position has to be expected for the S1 DRG. Intraspinal position of L4 and L5 DRG renders them more susceptible to compression from a superior articular facet or a bulging disc. Cases of extraforaminal positions of dorsal root ganglia have been reported at L4 and L5 levels. On its recurrent course through the lateral canal, the sinuvertebral nerve(s) supplies the laterodorsal outer annulus of the intervertebral disc, the PLL, the anterior 2/3 of the dural sac and the anterior vascular plexus. Many blood vessels pass through the lateral neural canal: the anterior and posterior spinal canal branches, anterior and posterior radicular branches, and veins of the anterior and posterior internal vertebral venous plexus. Per segment, one or two thick and one to four thin sinuvertebral nerves (SVN) originate from rami communicantes close to the connection of the latter to the spinal nerve. The extensive ramifications of the thin SVNs complete a thorough network at the floor of the central lumbar canal. A large part of it supplies the PLL. The PLL is assumed to play an important role in proprio- and nociception. It is probably one of the first structures to mediate nociceptive information from disc tissue. After injection of neuronal tracers into the sympathetic trunk at L3-L4 in rats, labeled cells were found in higher DRGs as well as labeled nerve fibers in the dura mater at lower levels. These findings indicate both a segmental and a non segmental pathway of sensory innervation of the dura mater and a role of higher DRGs in mediating LBP. In the neighborhood of the SVN, other small branches emanate from the rami communicantes and join the dorsal ramus and the segmental artery that enters the neural canal. The sympathetic nerve plexus inside the anterior longitudinal ligament and the SNVs provide a network of nerve fibers around the vertebral bodies and intervertebral discs. These pathways explain the sympathetic component of the innervation of a number of spinal structures. The dorsal ramus

innervates the facet joints at the corresponding level and one below, before it gives off muscular and cutaneous branches

Anatomical and radiologic studies on the lumbosacral meningo-vertebral ligaments of humans.

J Spinal Disord. 1990 Mar;3(1):6-15. R Scapinelli.

Among the minor soft structures of the lumbosacral spinal canal that computed tomography can visualize, the meningo-vertebral ligaments have been neglected. There are no specific reports on this subject, and the only knowledge we have comes from very ancient and nearly forgotten anatomical works. From our studies on cadaveric specimens, it has been confirmed that the ligaments consist segmentally of ventral and lateral fibrous bands, connecting the outer surface of the dura to the endostium of the spinal canal. The most characteristic component is the ventral one, running from the anterior wall of the dural sac to the posterior longitudinal ligament and vertebral endostium. Due to their anchoring function, the ligaments are significantly developed at the level of the dural conus (sacro-dural ligaments of Trolard and Hofmann). On in vivo computed tomography studies, the ligament image appears most commonly on transverse scanograms of the lumbosacral segments as a median sagittal septum, easily identifiable when the extradural fat that it crosses is abundant. The meningo-vertebral ligaments may be implicated in pathological conditions of the spinal canal. They can calcify singly, though very rarely, and this process must be differentiated from degenerative marginal spurs, calcific disc herniation, circumscribed calcification of the posterior longitudinal ligament, or partial diplomyelia.

Anterior sacro-dural attachments – Trolard's ligaments revisited.

Man Ther. 1996 Mar;1(2):88-91. E Barbaix, M D Girardin, J P Hoppner, P Van Roy, J P Clarijs.

In contrast to the attention paid to the structures surrounding spinal nerve roots in the intervertebral foramina, the anterior dural attachments are largely ignored, although they have been described since the last decades of the 19th century. These anterior attachments were systematically studied in a series of 30 cadaver dissections and were found to be present in almost 94% of cases. Four types of anterior attachments were observed. The most frequent form (84%) being a system of filaments that present as a double cross vault between the dura mater and the posterior longitudinal ligament extending from L3 to S3 levels. Less frequent were sagittal filaments (30%), short strong ligaments (17%) and a median septum from L3 to the end of the dural sac (7%). No attachments were found in two cadavers. Further studies are needed to clarify the possible role of these structures in transmitting movement to the dural sac and periradicular sleeves when mobilising the last three lumbar vertebrae or the sacrum.

The Filum Terminale Revisited: A Histological Study in Human Fetuses.

Pediatr Neurosurg. 2016;51(1):9-19. Hyung Suk Jang, Kwang Ho Cho, Hyuk Chang, Zhe Wu Jin, Jose Francisco Rodriguez-Vazquez, Gen Murakami.

Previous studies have suggested that secondary neurulation provides no functional neurons but only the filum terminale. However, no studies have confirmed that the coccygeal and lower sacral nerves do not originate from the secondary neural tube but only from the primary tube. To obtain a better understanding of these relationships, we examined sagittal or frontal sections from 20 embryonic and fetal specimens ranging from 6 to 14 weeks of gestation. During the growth of the vertebral column as well as the subsequent upward migration of the caudal end of the dural sac, the secondary neural tube was stretched to maintain the original attachment to the coccyx or the lower sacral vertebra. The filum-like structure showed much individual variability but in all cases appeared to be derived from the stretched neural tube. Intermediate age morphology revealed that the secondary neural tube itself provided an initial filum terminale before the ascent of the dural sac. Given that the coccygeal and lower sacral nerves are likely to originate from the secondary neural tube, these parts of the tube persisted and differentiated into spinal neurons to form the anococcygeal nerves. Likewise, the filum terminale was also most likely to contain some neurons that persisted postnatally. Depending on the timing and site of degeneration of the secondary neural tube, individual variations could occur in proportion to the amount of sensory and motor elements in the anococcygeal nerve supply.

Gross and microscopic study of the filum terminale: does the filum contain functional neural elements?

J Neurosurg Pediatr. 2012 Jan;9(1):86-92. Samson Sujit Kumar Gaddam, Vissa Santhi, Srinivasa Babu, Geeta Chacko, Ramakrishna Appala Baddukonda, Vedantam Rajshekhar.

Object: The filum terminale (FT) is considered a fibrous structure that extends from conus medullaris of the spinal cord to coccyx. Based on previous studies and from their own experience with intraoperative electrophysiological monitoring of the sacral nervous system, the authors postulate that the FT contains functional neural elements in some individuals.

Methods: The FT was dissected from 13 fresh stillborn cadavers (7 male, 6 female; mean gestational age 36 weeks and 1 day). The gross anatomical features were recorded, and connections between the FT and the nerve roots of the cauda equina were noted. These connections, when present, were sectioned for histological studies. The fila (both interna and externa) were also sectioned for histological and immunohistochemical studies. In addition, FT specimens were obtained from 5 patients undergoing sectioning of the FT in an untethering surgical procedure.

Results: There were 5 gross connections between the FT and nerve roots demonstrating nerve fibers that were positive for S100. The FT showed islands of cells that were positive for GFAP in 10 cases, synaptophysin in 3 cases, S100 in 11 cases, and nestin in 2 cases. The nerve fibers in the FT were myelinated in 2 cases. The conus ended at

the L-1 or L-2 vertebral level in all 13 specimens. The dural sac terminated at the S-2 vertebral level in most of the specimens. The 5 FT specimens that were obtained from patients revealed nerve bundles that were positive for S100 in 4 cases and cells that were positive for GFAP in 3 cases.

Conclusions: There are gross anatomical connections between the FT and nerve roots that contain nerve fibers. Apart from fibrous stroma, the FT may contain nerve bundles and cells that stain positive for GFAP, synaptophysin, S100, and nestin. **These microscopic findings and previous intraoperative electrophysiological studies suggest a probable functional role for the FT in some individuals.** At birth, the conus ends at a higher vertebral level (lower L-1 or upper L-2) than L-3.

A comparative study of histopathological analysis of filum terminale in patients with tethered cord syndrome and in normal human fetuses.

Pediatr Neurosurg. 2011;47(6):412-6. Ozkan Tehli, Irgen Hodaj, Cahit Kural, Ilker Solmaz, Onder Onguru, Yusuf Izci.

Background: **The structural changes in filum terminale (FT) may be responsible for tethered cord syndrome (TCS) in children.** Although the histological changes in FT related to TCS are well-known, there is no comparative study of the changes which occur in TCS and normal fetal FT samples. The aims of this study are to compare the histological changes which occurred in FT samples of TCS and in fetuses, and to point out these changes.

Methods: During the last 2 years, 14 cases of TCS were operated on, the FT was cut and the spinal cord was released. Among them, 6 samples of FT were obtained for histopathological examination. Moreover, 1 FT from an adult cadaver and 4 samples from fetal FT were obtained for the same examination.

Results: While adipose tissue, fibrosis, hyalinization, and meningotheial proliferation were observed in FT samples of TCS, none of these findings were observed in fetal samples. Elastic fibers were present in all TCS specimens and the adult cadaver, but were not observed in fetuses. Peripheral nerves, ganglion cells and ependymal cells were observed in fetal FT samples.

Conclusion: These changes probably begin at birth.

Adverse mechanical tension in the central nervous system: an analysis of cause and effect: relief by functional neurosurgery.

Book. New York: Wiley; 1978. Breig, Alf,

The denticulate ligament: anatomical properties, functional and clinical significance.

Acta Neurochir (Wien). 2012 Jul;154(7):1229-34. Davut Ceylan, Necati Tatarlı, Tuychiboy Abdullaev, Aşkın Şeker, Sercan D Yıldız, Evren Keleş, Deniz Konya, Yaşar Bayri, Türker Kiliç, Safiye Çavdar.

Background: **It is widely believed that the main function of denticulate ligaments (DLs) is to stabilize the spinal cord within the vertebral canal.** The aim of this study was to assess the anatomical and histological structure of the DLs and to document any regional differences.

Methods: Five formalin-fixed adult cadavers were used. The DLs were exposed via the posterior approach, and detailed anatomy and histology of these structures were documented.

Results: **The main findings were: (1) each DL is composed of a single narrow fibrous strip that extends from the craniovertebral junction to T12, and each also features 18-20 triangular extensions that attach to the dura at their apices; (2) the triangular extensions are smaller and more numerous at the cervical levels, and are larger and less numerous at the thoracic levels; (3) the apices of the extensions attach to the dura via fibrous bands at cervical levels (each band 3-5 mm long) and lower thoracic levels (21-26 mm long), whereas they attach directly to the dura at upper thoracic levels; (4) the narrow fibrous strip of the DL features longitudinally oriented collagen fibers, whereas the triangular extensions are composed of transverse and obliquely oriented collagen fibers. The collagen fibers are thicker and more abundant at the cervical than at the thoracic levels.**

Conclusion: DL histology and anatomy are strongly correlated with the function of this structure at different spinal levels. It is important to have accurate knowledge about DLs as these structures are relevant for clinical procedures that involve the spinal cord or craniovertebral junction.

A review of biomechanics of the central nervous system – part II: spinal cord strains from postural loads.

J Manipulative Physiol Ther. 1999 Jun;22(5):322-32. D E Harrison, R Cailliet, D D Harrison, S J Troyanovich, S O Harrison.

Objective: To review spinal cord strains arising from postural loads.

Data collection: A hand search of available reference texts and a computer search of literature from the Indexed Medicus sources were collected, with special emphasis placed on spinal cord strains caused by various postural rotations and translations of the skull, thorax, and pelvis

Results: **All spinal postures will deform the neural elements within the spinal canal. Flexion causes the largest canal length changes and, hence, the largest nervous system deformations. Neural tissue strains depend on the spinal level, the spinal movement generated, and the sequence of movements when more than one spinal area is moved.**

Conclusions: Rotations of the global postural components (head, thoracic cage, pelvis, and legs) cause stresses and strains in the central nervous system and peripheral nervous system. Translations of the skull, thorax, and pelvis, as well as combined postural loads, need to be studied for their effects on the spinal canal and neural tissue deformations. Flexion of any part of the spinal column may generate axial tension in the entire cord and nerve roots. Slight extension is the preferred position of the spine as far as reducing the magnitude of mechanical stresses and strains in the central nervous system is concerned.

Dynamic studies of cervical spinal canal and spinal cord by magnetic resonance imaging.

Acta Radiol Suppl. 1986;369:727-9. F Koschorek, H P Jensen, B Terwey.

In 15 cases dynamic studies of cervical spinal cord and canal in flexion and extension were performed by magnetic resonance imaging (MRI). In addition measurements of the complete spinal cord were made in 5 cases. As compared with extension the cervical spinal canal and spinal cord lengthen 12 mm in average during flexion, whereas the spinal canal lengthens 28 mm in average, which means a difference of about 15 mm. We feel that these results indicate that adverse mechanical tension may occur in the cervical spinal cord during flexion. The impact of these results on surgical treatment for chronic cervical myelopathy is discussed.

Stretch-associated injury in cervical spondylotic myelopathy: new concept and review.

Neurosurgery. 2005 May;56(5):1101-13. Fraser C Henderson, Jennian F Geddes, Alexander R Vaccaro, Eric Woodard, K Joel Berry, Edward C Benzel.

The simple pathoanatomic concept that a narrowed spinal canal causes compression of the enclosed cord, leading to local tissue ischemia, injury, and neurological impairment, fails to explain the entire spectrum of clinical findings observed in cervical spondylotic myelopathy. A growing body of evidence indicates that spondylotic narrowing of the spinal canal and abnormal or excessive motion of the cervical spine results in increased strain and shear forces that cause localized axonal injury within the spinal cord. During normal motion, significant axial strains occur in the cervical spinal cord. At the cervicothoracic junction, where flexion is greatest, the spinal cord stretches 24% of its length. This causes local spinal cord strain. In the presence of pathological displacement, strain can exceed the material properties of the spinal cord and cause transient or permanent neurological injury. Stretch-associated injury is now widely accepted as the principal etiological factor of myelopathy in experimental models of neural injury, tethered cord syndrome, and diffuse axonal injury. Axonal injury reproducibly occurs at sites of maximal tensile loading in a well-defined sequence of intracellular events: myelin stretch injury, altered axolemmal permeability, calcium entry, cytoskeletal collapse, compaction of neurofilaments and microtubules, disruption of anterograde axonal transport, accumulation of organelles, axon retraction bulb formation, and secondary axotomy. Stretch and shear forces generated within the spinal cord seem to be important factors in the pathogenesis of cervical spondylotic myelopathy.

Cervical laminectomy and dentate ligament section for cervical spondylotic myelopathy.

J Spinal Disord. 1991 Sep;4(3):286-95. E C Benzel, J Lancon, L Kesterson, T Hadden

Seventy-five patients who underwent surgical treatment for cervical spondylotic myelopathy were evaluated with respect to the operative procedure performed and their outcome. Forty patients underwent a laminectomy plus dentate ligament section (DLS), 18 underwent laminectomy alone, and 17 underwent an anterior cervical decompression and fusion (ACDF). The patients were evaluated postoperatively for both stability and for neurologic outcome using a modification of the Japanese Orthopaedic Association Assessment Scale. Functional improvement occurred in all but one patient in the laminectomy plus DLS group. The average improvement was 3.1 +/- 1.5 points in this group; whereas the average improvement in the laminectomy and the ACDF groups was 2.7 +/- 2.0 and 3.0 +/- 2.0 points respectively. All of the patients who improved substantially (greater than or equal to 6 points) in the laminectomy plus DLS and the laminectomy alone groups had normal cervical spine contours (lordosis). The remainder had either a normal lordosis or no curve (no kyphosis or lordosis). All patients in the ACDF group had either a straight spine or a cervical kyphosis. These factors implicate spine curvature, in addition to choice of operation, as factors which are important in outcome determination. No problems with instability occurred in either the laminectomy or the laminectomy plus DLS group. Two patients incurred problems with stability in the ACDF group. Both required reoperation. In addition, four patients in this group who initially improved, subsequently deteriorated. Six patients in the laminectomy plus DLS group had a several day febrile episode related to an aseptic meningitis process. Laminectomy plus DLS is a safe and efficacious alternative to laminectomy for the treatment of cervical spondylotic myelopathy. The data presented here suggests that myelopathic patients with a cervical kyphosis are best treated with an ACDF and that patients with a normal cervical lordosis are best treated with a posterior approach. Although some selected patients may benefit from DLS, no criteria are available which differentiate this small subset of patients.

In vivo human cervical spinal cord deformation and displacement in flexion.

Spine (Phila Pa 1976). 1998 Aug 1;23(15):1677-83. Q Yuan, L Dougherty, S S Margulies.

Study design: In vivo, quasi-static distortion of the human cervical spinal cord was measured in five volunteers during flexion of the neck using a motion-tracking magnetic resonance imaging technique.

Objectives: To measure cord distortion and movement in living subjects.

Summary of background data: In situ spinal cord measurements in human and rhesus monkey cadavers taken at full flexion demonstrate that the entire cervical cord elongates approximately 10% of its length at a neutral position, but no data are available at other angles of flexion, or in living subjects.

Methods: The spatial modulation of magnetization pulse sequence created a series of parallel lines in the image that deform with the tissue. A custom-designed device was built to guide the flexion of the neck and enhance motion reproducibility. Midsagittal plane images were acquired before and after flexion. The tagged line pattern in each pair of magnetic resonance images was compared to compute distortion and movement of the cervical spinal cord at varying degrees of flexion.

Results: Between a neutral posture and full flexion, the entire cord (C2-C7) elongated linearly with head flexion, increasing 10% and 6% of its initial length along the posterior and anterior surfaces, respectively. Average displacement was on the order of 1-3 mm, and varied with region. Specifically, the upper cord showed caudad movement in the spinal canal, and the lower cord moved cephalad, again with larger movements on the posterior surface.

Conclusions: The cervical cord elongates and displaces significantly during head flexion in human volunteers, offering valuable information regarding the normal milieu of the cord.

Measurement of in vivo spinal cord displacement and strain fields of healthy and myelopathic cervical spinal cord.

J Neurosurg Spine. 2019 Mar 22;31(1):53-59. Kirsten E Stoner, Kingsley O Abode-Iyamah, Vincent A Magnotta, Matthew A Howard, Nicole M Grosland.

Objective: Cervical myelopathy (CM) is a common and debilitating form of spinal cord injury caused by chronic compression; however, little is known about the in vivo mechanics of the healthy spinal cord during motion and how these mechanics are altered in CM. The authors sought to measure 3D in vivo spinal cord displacement and strain fields from MR images obtained during physiological motion of healthy individuals and cervical myelopathic patients.

Methods: Nineteen study participants, 9 healthy controls and 10 CM patients, were enrolled in the study. All study participants had 3T MR images acquired of the cervical spine in neutral, flexed, and extended positions. Displacement and strain fields and corresponding principal strain were obtained from the MR images using image registration.

Results: The healthy spinal cord displaces superiorly in flexion and inferiorly in extension. Principal strain is evenly distributed along the spinal cord. The CM spinal cord displaces less than the healthy cord and the magnitude of principal strain is higher, at the midcervical levels.

Conclusions: Increased spinal cord compression during cervical myelopathy limits motion of the spinal cord and increases spinal cord strain during physiological motion. Future studies are needed to investigate how treatment, such as surgical intervention, affects spinal cord mechanics.

Pathogenesis of cervical spondylotic myelopathy.

J Neurol Neurosurg Psychiatry. 1997 Apr;62(4):334-40. D N Levine.

Objective: To determine whether either of two mechanical theories predicts the topographic pattern of neuropathology in cervical spondylotic myelopathy (CSM). The compression theory states that the spinal cord is compressed between a spondylotic bar anteriorly and the ligamenta flava posteriorly. The dentate tension theory states that the spinal cord is pulled laterally by the dentate ligaments, which are tensed by an anterior spondylotic bar.

Methods: The spinal cord cross section, at the level of a spondylotic bar, is modelled as a circular disc subject to forces applied at its circumference. These forces differ for the two theories. From the pattern of forces at the circumference the distribution of shear stresses in the interior of the disc—that is, over the transverse section of the spinal cord—is calculated. With the assumption that highly stressed areas are most subject to damage, the stress pattern predicted by each theory can be compared to the topographic neuropathology of CSM.

Results: The predicted stress pattern of the dentate tension theory corresponds to the reported neuropathology, whereas the predicted stress pattern of the compression theory does not.

Conclusions: The results strongly favour the theory that CSM is caused by tensile stresses transmitted to the spinal cord from the dura via the dentate ligaments. A spondylotic bar can increase dentate tension by displacing the spinal cord dorsally, while the dural attachments of the dentate, anchored by the dural root sleeves and dural ligaments, are displaced less. The spondylotic bar may also increase dentate tension by interfering locally with dural stretch during neck flexion, the resultant increase in dural stress being transmitted to the spinal cord via the dentate ligaments. Flexion of the neck increases dural tension and should be avoided in the conservative treatment of CSM. Both anterior and posterior extradural surgical operations can diminish dentate tension, which may explain their usefulness in CSM. The generality of these results must be tempered by the simplifying assumptions required for the mathematical model.

A review of the pathophysiology of cervical spondylotic myelopathy with insights for potential novel mechanisms drawn from traumatic spinal cord injury.

Spine (Phila Pa 1976). 1998 Dec 15;23(24):2730-7. M G Fehlings, G Skaf.

Cervical spondylotic myelopathy (CSM) is the most common cause of spinal cord dysfunction. Despite advances in diagnosis and surgical treatment, many patients still have severe permanent neurologic deficits caused by this

condition. An improved understanding of the pathophysiology of cervical spondylotic myelopathy, particularly at a cellular and molecular level, may allow improved treatments in the future. A detailed review of articles in the literature pertaining to cervical spondylotic myelopathy was supplemented by an analysis of relevant mechanisms of spinal cord injury. The pathologic course of cervical spondylotic myelopathy is characterized by early involvement of the corticospinal tracts and later destruction of anterior horn cells, demyelination of lateral and dorsolateral tracts, and relative preservation of anterior columns. Static and mechanical factors and ischemia are critical to the development of cervical spondylotic myelopathy. Free radical-and cation-mediated cell injury, glutamatergic toxicity, and apoptosis may be of relevance to the pathophysiology of cervical spondylotic myelopathy. To date, research in cervical spondylotic myelopathy has focused exclusively on the role of mechanical factors and ischemia. Fundamental research at a cellular and molecular level, particularly in the areas of glutamatergic toxicity and apoptosis may result in clinically relevant treatments for this condition.

Spinal cord distraction: an in vitro study of length, tension, and tissue pressure.

J Spinal Disord. 1991 Jun;4(2):177-82. P F Jarzem, J P Kostuik, M Filiaggi, D J Doyle, R Ethier, C H Tator.

Since the Scoliosis Research Society released a report on cord injury related to Harrington rod instrumentation for scoliosis, little has been published on the pathophysiology of this disorder. Dolan et al. described diminished cord blood flow associated with spinal distraction in a cat model, but failed to demonstrate its cause. In this article, we describe a series of in vitro experiments performed on dog and sheep cadaver spinal cords. Controlled distractive forces were applied to spinal cords while monitoring both cord interstitial pressure and cord elongation. A close ($R_{avg} = 0.986$) correlation was noted between applied tensile forces and cord interstitial pressure. At 1,000-g loads, the average tissue pressure obtained was 29.5 cm H₂O, ranging from 17 to 47 cm H₂O. However, it was noted that the cord demonstrated nonlinear tensile elastic properties that appeared exponential in the range examined. These properties are consistent with those described for collagen-containing compounds. We conclude that spinal cord distraction is capable of generating cord tissue pressures that could cause a spinal cord compartment syndrome and thereby seriously impair spinal cord blood flow causing spinal cord injury.

The Nicolas Andry Award. The pathomechanics and pathophysiology of cervical spinal cord injury.

Clin Orthop Relat Res. 1995 Dec;(321):259-69. J S Torg, L Thibault, B Sennett, H Pavlov.

Cervical cord injuries caused during American football games have resulted in reversible, incompletely reversible, and irreversible neurologic deficits. An explanation for this variable response to injury has been obtained from the study of the histochemical responses of a squid axon injury model to mechanical deformation. Data obtained indicate that recovery or lack thereof is directly proportional to the intracellular calcium concentration which in turn is directly proportional to the amount and rate of tension applied to the axon. It is concluded that in most instances of acute spinal injury, disruption of cord function is a result of the effects of local cord anoxia and the increased concentration of intracellular calcium. It is proposed that implementation of therapeutic measures that restore blood flow and reduce cytosolic calcium will increase neurologic recovery.

Pathophysiology of tethered cord syndrome: correlation with symptomatology.

Neurosurg Focus. 2004 Feb 15;16(2):E6. Shokei Yamada, Daniel J Won, Shoko M Yamada.

Tethered cord syndrome (TCS) is a stretch-induced functional disorder of the spinal cord. The mechanical cause of TCS is an inelastic structure anchoring the caudal end of the spinal cord that prevents cephalad movement of the lumbosacral cord. Stretching of the spinal cord occurs in patients either when the spinal column grows faster than the spinal cord or when the spinal cord undergoes forcible flexion and extension. Research in patients and experimental animals suggests that there is a link between the clinical dysfunctions that characterize TCS and putative pathophysiological changes that accompany this syndrome. Among these changes are depression of electrophysiological activity and shifts in the reduction/oxidation ratio of cytochrome oxidase. The latter suggests that there is impairment of oxidative metabolism. These putative pathophysiological changes in TCS occur mainly within the lumbosacral cord under excessive tension. The authors discuss the pathophysiology of TCS and examine related symptoms.

Mechanical and physiological effects of dentatotomy.

J Neurosurg. 1977 Jun;46(6):767-75. J F Cusick, J J Ackmann, S J Larson.

The role of the dentate ligaments in the pathogenesis of myelopathy secondary to disease conditions that alter the normal biomechanics of the spinal canal was studied in 14 dogs. The effects of posterior cord elevation on somatosensory evoked potentials (SSEP's) and tension requirements were compared before and after dentate ligaments section in acute experiments. At levels of posterior elevation usually within the confines of the canine canal, the dentate ligaments were the most significant element increasing tension requirements and SSEP alternations. Human cadaver studies also showed an approximate 50% reduction of force after dentatotomy. These findings suggests that after dentate ligaments section the applied tension is distributed over a longer segments of the cord with a reduction in tension and disruption of axonal conduction at the level at which the force was applied.

Pathophysiology of adult tethered cord syndrome: review of the literature.

Neurosurg Focus. 2010 Jul;29(1):E2. William R Stetler Jr, Paul Park, Stephen Sullivan.

Object: Tethering of the spinal cord has been a recognized cause of neurological symptoms in pediatric patients and is increasingly being recognized as a cause of symptoms in adults as well. The pathophysiology surrounding spinal cord tethering has begun to be understood in the pediatric population but is still unclear in adult patients.

Methods: Using a PubMed database literature search, the authors reviewed the pathology and pathophysiology surrounding the tethered spinal cord, focusing particularly on the pathophysiology of adult tethered cord syndrome (TCS).

Results: Experimental data obtained in pediatric patients at surgery and in animal models indicate that spinal cord tethering causes a reduction in spinal cord blood flow and dysfunction of neuronal mitochondrial terminal oxidase. Retrospective analyses of patients undergoing surgery for adult TCS show that many adults developed symptoms following an event that could stretch the spinal cord, while others did not. Many patients also were found to have structural lesions in addition to a tethered spinal cord at diagnosis.

Conclusions: Both adult and pediatric TCSs are likely the result of a relative lack of blood flow to the spinal cord, causing dysfunction in mitochondrial oxidative phosphorylation. The likely reason the syndrome present later and differently in adults is that a secondary threshold of tension or a cumulative effect of repetitive, transient tension is placed on the cord before symptoms are recognized.

Spinal cord traction, vascular compromise, hypoxia, and metabolic derangements in the pathophysiology of tethered cord syndrome.

Neurosurg Focus. 2010 Jul;29(1):E9. Aristotelis S Filippidis, M Yashar Kalani, Nicholas Theodore, Harold L Rekate.

Object: The definition of tethered cord syndrome (TCS) relies mainly on radiological criteria and clinical picture. The presence of a thickened filum terminale and a low-lying conus medullaris in symptomatic patients is indicative of TCS. The radiological definition of TCS does not take into account cases that involve a normal-lying conus medullaris exhibiting symptoms of the disease.

Methods: The authors performed a MEDLINE search using the terms "tethered cord" and "pathophysiology." The search returned a total of 134 studies. The studies were further filtered to identify mostly basic research studies in animal models or studies related to the biomechanics of the filum terminale and spinal cord.

Results: Spinal cord traction and the loss of filum terminale elasticity are the triggers that start a cascade of events occurring at the metabolic and vascular levels leading to symptoms of the disease. Traction on the caudal cord results in decreased blood flow causing metabolic derangements that culminate in motor, sensory, and urinary neurological deficits. The untethering operation restores blood flow and reverses the clinical picture in most symptomatic cases.

Conclusions: Although classically defined as a disease of a low-lying conus medullaris, the pathophysiology of TCS is much more complex and is dependent on a structural abnormality, with concomitant altered metabolic and vascular sequelae. Given the complex mechanisms underlying TCS, it is not surprising that the radiological criteria do not adequately address all presentations of the disease.

What is the true tethered cord syndrome?

Childs Nerv Syst. 2007 Apr;23(4):371-5. Shokei Yamada, Daniel J Won.

Introduction: The tethered cord syndrome (TCS) is a stretch-induced functional disorder of the spinal cord with its caudal part anchored by an inelastic structure.

Discussion: This article clarifies the reversible lesions that occur in the cord segments above any of the inelastic abnormalities. These lesions are found mostly in the lumbosacral cord, occasionally in the cervical cord and closely correlate with clinical findings. Imaging studies alone do not allow accurate diagnosis of the TCS. The authors emphasize the importance of adhering to the physiological terms "tethered cord syndrome" and "tethered spinal cord" to avoid controversies derived from terms that are not based on the pathophysiology of TCS.

Pathophysiology of tethered cord syndrome and other complex factors.

Neurol Res. 2004 Oct;26(7):722-6. Shokei Yamada, David S Knerium, George M Mandybur, Robert L Schultz, Brian S Yamada.

There are different interpretations of tethered cord syndrome (TCS) partly due to difficulty in understanding the concept of this syndrome as a functional disorder not merely based on gross anatomy of congenital anomalies. The essential mechanical factor of cord tethering is that any of the inelastic structures fastening the caudal end of the spinal cord produces traction effects on the lumbosacral cord. The production of such traction is the key to understanding this disorder. In a significant number of patients who present with the typical clinical signs and symptoms of TCS, the diameter of the filum terminale is found within normal limits and the caudal end of the spinal cord is located in the normal position. Therefore, the definition of TCS requires the demonstration that there is a posterior displacement of the conus and filum by MRI, lack of viscoelasticity by the stretch test of the filum during surgery, and fibrous displacement of glial tissue within the filum by histological studies. This is because there is inconsistency from such studies as ultrasonography, MRI and CT myelography, which attempt to establish the presence of a tight filum terminale. A goal of this article is to provide basic understanding of TCS so that clinicians can use the concept of stretch-induced spinal cord dysfunction for proper diagnosis and treatment of this disorder.

Is Intervertebral Disc Degeneration a Compensatory Mechanism in Adult Tethered Cord Syndrome?

World Neurosurg. 2023 Jul;175:e511-e519. Zhuang Zhang, Hengrui Chang, Kaiyu Liu, Di Zhang, Rui Xue, Haoran Li, Zhaoxuan Wang, Guzhen Liang, Xianzhong Meng.

Objective: The purpose of the present study was to evaluate the influence of high nerve tension on lumbar disc degeneration and sagittal morphologies.

Materials and methods: A total of 50 young and middle-aged patients (mean age 32.1 ± 7.4 years, 22 men and 28 women) who suffered from tethered cord syndrome (TCS) were retrospectively assessed by two observers. Demographic and radiological data were recorded, including lumbar disc degeneration, disc height index and lumbar spine angle, and were compared with 50 patients (mean age 29.7 ± 5.4 years, 22 men and 28 women) without spinal cord abnormalities. Statistical associations were assessed by student's t-test and chi-square test.

Results: Our results showed patients with TCS had a significantly higher rate of lumbar disc degeneration in L1/2, L2/3, L4/5 and L5/S1 than in those without TCS ($P < 0.05$). Moreover, the rates of multilevel disc degeneration and severe disc degeneration in TCS group were significantly higher than those in control group ($P < 0.01$). The mean disc height index of L3/4 and L4/5 in TCS group was significantly lower than that in control group ($P < 0.05$). The mean lumbosacral angle of TCS patients was significantly higher than that of patients without TCS ($38.4 \pm 3.5^\circ$ vs. $33.7 \pm 5.9^\circ$, $P < 0.01$).

Conclusions: We found a certain correlation between TCS and lumbar disc degeneration and lumbosacral angle enlargement, suggesting that the spine reduces the high tension of the spinal cord through disc degeneration.

Therefore, it is speculated that there is a "compromised regulation" mechanism in the body under the condition of neurological abnormalities.

Analysis of correlation between spinal nerve high tension and disc degeneration in 100 cases.

Zhonghua Yi Xue Za Zhi. 2017 Nov 21;97(43):3416-3420. Q J Kong, X M Xu, J C Sun, Y Wang, G D Shi, Y F Guo, H S Yang, Y Yang, J G Shi.

Objective: To explore the correlation between the spinal nerve high tension and lumbar disc degeneration, the pathogenesis of hanging intervertebral disc degeneration.

Methods: From June 2016 to June , a retrospective analysis 2017 of 100 cases of lumbar spinal stenosis were included in Department of Spine Surgery, Changzheng Hospital, the Second Military Medical University. They were divided into experimental group (50 cases, nerve high tension group) and control group (50 cases, nervous tension in the normal group) according to preoperative lumbar MRI of cauda equina syndrome and settlement of intraoperative detecting nerve tension. The Pfirrmann grade was used to evaluate degree of lumbar (L3/4-L5/S1) disc degeneration. The correlation between spinal nerve tension and lumbar disc degeneration was analyzed, and the severity of experimental group and control group on lumbar disc degeneration was compared.

Results: There was no significant difference in the age and sex ratio between the two groups ($P > 0.05$). The Pfirrmann score of the experimental group was L3/4 (4.74 ± 1.6) grade, L4/5 (5.32 ± 1.33) grade, L5/S1 (5.54 ± 1.13) grade; the control group Pfirrmann score was L3/4 (3.5 ± 1.16) grade, L4/5 (4.12 ± 0.9) grade, and L5/S1 (4.1 ± 0.97) grade. The severity of intervertebral disc degeneration in experimental group was higher than that in control group, with statistical significance ($P < 0.05$). There was a correlation between lumbar disc degeneration and nerve tension in L3/4, L4/5 and L5/S1, and the correlation trend was $L5/S1 > L4/5 > L3/4$.

Conclusion: There is a correlation between lumbar disc degeneration and spinal nerve high tension. A new pathogenesis of hanging intervertebral disc degeneration that the degeneration of lumbar disc is a compensatory mechanism in order to alleviate the axial stretch injury is put forward.

Nonlinear switching dynamics in surface electromyography of the spine.

2003 International Conference Physics and Control. Proceedings. 20-22 Aug. 2003. P. Lohsoonthorn; E. Jonckheere

This paper develops a switching dynamics model of the surface Electromyographic (sEMG) signal generated during a condition in which the mechanical attachment of the spinal dura to the cervical vertebra creates an unstable nonlinear feedback coupling between the biomechanics of the spine and the central nervous system (CNS). The sEMG signal recorded on the paraspinal muscles during this condition reveals "bursts" of accrued sEMG activity interrupting an otherwise quiet "background" signal. Statistical analysis of the autocorrelation and partial correlation functions of the burst and background parts of the signal reveals that the over-all signal indeed switches between two modes. Both the burst and the background modes are dynamically modeled by ARIMA and ACE, and a switching logic, driven by the autocorrelation and the partial correlation, is designed, resulting in a switching model that matches the experimental sEMG signal fairly well.

Cerebrospinal fluid stasis and its clinical significance.

Altern Ther Health Med. 2009 May-Jun;15(3):54-60. James M Whedon, Donald Glassey.

We hypothesize that stasis of the cerebrospinal fluid (CSF) occurs commonly and is detrimental to health. Physiologic factors affecting the normal circulation of CSF include cardiovascular, respiratory, and vasomotor influences. The CSF maintains the electrolytic environment of the central nervous system (CNS), influences systemic acid-base balance, serves as a medium for the supply of nutrients to neuronal and glial cells, functions as a lymphatic system for the CNS by removing the waste products of cellular metabolism, and transports hormones, neurotransmitters, releasing factors,

and other neuropeptides throughout the CNS. Physiologic impedance or cessation of CSF flow may occur commonly in the absence of degenerative changes or pathology and may compromise the normal physiologic functions of the CSF. CSF appears to be particularly prone to stasis within the spinal canal. CSF stasis may be associated with adverse mechanical cord tension, vertebral subluxation syndrome, reduced cranial rhythmic impulse, and restricted respiratory function. Increased sympathetic tone, facilitated spinal segments, dural tension, and decreased CSF flow have been described as closely related aspects of an overall pattern of structural and energetic dysfunction in the axial skeleton and CNS. Therapies directed at affecting CSF flow include osteopathic care (especially cranial manipulation), craniosacral therapy, chiropractic adjustment of the spine and cranium, Network Care (formerly Network Chiropractic), massage therapy (including lymphatic drainage techniques), yoga, therapeutic breath-work, and cerebrospinal fluid technique. Further investigation into the nature and causation of CSF stasis, its potential effects upon human health, and effective therapies for its correction is warranted.

Dura Mater: Anatomy and Clinical Implication.

Journal of Behavioral and Brain Science, 2021, 11, 239-247. Mehmet Ünal, Ahmet Burak Sezgin.

https://www.researchgate.net/publication/354959013_Dura_Mater_Anatomy_and_Clinical_Implication