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# Lateral epicondylosis: A literature review to link pathology and tendon function to tissue-level treatment and ergonomic interventions

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ABSTRACT

*Background:* Common treatments for lateral epicondylosis (LE) focus on tissue healing. Ergonomic advice is suggested broadly, but recommendations based on biomechanical motion parameters associated with functional activities are rarely made. This review analyzes the role of body functions and activities in LE and integrates the findings to suggest motion parameters applicable to education and interventions relevant to activities and life roles for patients.

*Purpose:* This study examines LE pathology, tendon and muscle biomechanics, and population exposure outlining potentially hazardous activities and integrates those to provide motion parameters for ergonomic interventions to treat or prevent LE. A disease model is discussed to align treatment approaches to the stage of LE tendinopathy.

*Study Design:* Integrative review

*Methods:* We conducted in-depth searches using PubMed, Medline, and government websites. All levels of evidence were included, and the framework for behavioral research from the National Institutes of Health was used to synthesize ergonomic research.

*Results:* The review broadened the diagnosis of LE from a tendon ailment to one affecting the enthesis of the capitellum. It reinforced the continuum of severity to encompass degeneration as well as regeneration. Systematic reviews confirmed the availability of evidence for tissue-based treatments, but evidence of well-defined harm reducing occupational interventions was scattered amongst evidence levels. Integration of biomechanical studies and population information gave insight into types of potentially hazardous activities and provided a theoretical basis for limiting hazardous exposures to wrist extensor tendons by reducing force, compression, and shearing during functional activities.

*Conclusions:* These findings may broaden the first treatment approach from a passive, watchful waiting into an active exploration and reduction of at-risk activities and motions. Including the findings into education modules may provide patients with the knowledge to lastingly reduce potentially hazardous motions during their daily activities, and researchers to define parameters of ergonomic interventions.



## Introduction

Lateral epicondylosis (LE) decreases the capacity to participate in activities essential to daily life. Based on a long career of caring for patients with LE, Nirschl[1] eloquently stated that “LE does not threaten the quantity of life, but it is a major impediment to the quality of life.”

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Many authors indicate that LE may be a self-limiting problem, that often resolves with time and limitation of painful activities, but 13% to 34% of patients treated in general practice still reported pain after 3 months or longer.[2] The Centers for Disease Control and Prevention (CDC) states that upper extremity musculoskeletal disorders, common in almost all sectors of the United States economy, are increasing in numbers along with associated costs to the worker and industry alike.[3] LE is no exception, with both the costs of care and surgical rates increasing as well.[4-6] Therefore, the search for cost-effective care of patients with LE remains great.

In many occupations higher prevalence rates are found than the reported rate in the general population of 0.7% to 4.0%.[7] In a review of 22 occupations, the highest prevalence was found in assembly line workers (20%). Other professions, also report high prevalence and incidence rates. Prevalence reached 13.5% in plastic surgeons[7,8] and 14% among reconstructive orthopedic surgeons, with the highest rate in those who regularly perform total hip replacements.[9] In sports, LE is most associated with tennis players,[10] but the condition is also listed as the most prevalent elbow injury in the leading arms of golfers[11-15] and in rock climbers.[16] Among musicians in general, LE prevalence has been reported to range from 39% to 87%.[17] Results from the University of North Texas Musician Health Survey (UNT-MHS) data set reported that pianists and organists were found most frequently to have problems with LE, followed by harpists.[18] There are also populations of athletes without LE as a primary diagnosis, where intuitively this might have been expected, such as throwing athletes and rowers.[19,20]

Abundant literature exists on various methods to enhance healing of the affected lateral elbow tissues.[21] Less abundantly, but increasing in frequency, are investigations into the painful and potentially harmful activities associated with lateral elbow pathology.[22] These studies typically focus on which types of activities are associated with the presence of LE; however, they rarely connect these activities to the structure and biomechanical function of lateral elbow tissues. Surveys show that ergonomic patient education for LE continues to be a key intervention used by hand therapists, occupational as well as physical therapists.[23,24] However, a scarcity of specifics to guide these educational and activity modification interventions was noted.[23]

The goal of this literature review is to explore, identify and integrate connections between tissue structures and function and activities, participation, environmental, and personal factors for the management of patients with LE, using the framework provided by the International Classification of Functioning, Disability and Health (ICF) by the World Health Organization. The ICF framework is suitable in its comprehensive approach to health problems.[24]

Connecting the biomechanics and pathology to specific motions during work, sports, and common daily activities will allow therapists, ergonomists, engineers in human factors, and medical personnel to educate patients on how to adapt activities to reduce the intensity, frequency, and duration of exposure to those activities.

## Methods

An explorative literature search was performed to justify the need for the study, identify and formulate the problem. Key constructs and keywords to serve the literature search were formulated. When a sparsity of systematic reviews was encountered to summarize the wide variation of ergonomic approaches, it was decided to use the framework for behavioral intervention development by the National Institutes of Health[25] to synthesize salient topics of ergonomic interventions for patients with LE. The study did not aim for a comprehensive review of evidence for tissue-level treatments but aimed to provide a brief review of the *mechanism* of tissue level treatments and commonly used applications presented in systematic investigations and randomized controlled studies from 2000 to 2021.

The following key constructs were identified and used as keywords: lateral epicondylosis, lateral epicondylitis, lateral epicondylalgia, tennis elbow, eECRB, incidence and prevalence, recovery and natural course, at-risk populations and occupations, work-related, sports, performing artists, anatomy, biomechanics and kinematics, neurosensory coordination, assessment and examination including imaging, ergonomics, adaptation, prevention, psychology, roles of occupational therapists and physical therapists in industry, ergonomics, participatory ergonomic programs, and review articles including history. The search did not focus on textbooks, but some hallmark textbooks were included.[26-28]

Data collections tables were created that included study purpose, study design and methods, study sample, intervention or exposures (when appropriate), type of measurement and results or outcomes. The detailed information in Tables 1 through 4 are listed in the appendix. A synthesis table, Table 5, was constructed to integrate the biomechanical and population exposure results into a set of defined harm reducing recommendations, and is presented in the results section.

## Results

### *Tissue involvement and tissue-level interventions*

#### *An anatomical landscape of the lateral elbow*

An in-depth description of elbow anatomy is provided by Morrey,[29] who describes the architecture of the osteology, elbow joint structures including their joint capsules and ligaments, bursae, vessels, nerves, and muscles in relation to topical anatomy. Figure 1 gives an overview of the elbow anatomy. The radial nerve is depicted as it traverses the elbow, including its innervated musculature surrounding the lateral epicondyle. The radial recurrent artery originates distally from the brachial artery, from where it penetrates the lateral intermuscular septum, accompanying the radial nerve, anastomosing at the level of the lateral epicondyle. The lateral collateral ligament reaches from the annular ligament through a Y shape into the anterior and posterior aspect of the semilunar notch.

The normal anatomical architecture of the tissues around the lateral epicondyle is complex and continues to be focus of study. Based on macroscopic and microscopic observations in 40 fresh-frozen cadavers, the tendons of the extensor carpi radialis brevis (ECRB) and extensor digitorum communis (EDC) were found to be indistinguishable at the osseotendinous origins.[30] The tendons were free from the underlying aponeurosis, loosely connected to the extensor carpi radialis longus (ECRL), and not embedded in the joint capsule. Connell et al.[31] described the close intertwining of fibrils forming the common extensor origin, with the fibers of the ECRB making up most of the articular side of the common extensor origin, and fibers of the EDC contributing to a lesser extent. The lateral collateral ligament is visible on sonography as a distinct and closely knitted fibrillated structure, deep in relation to ECRB and ECRL. Nimura[32] explained vulnerability of the ECRB because it was thin and purely tendinous at the insertion, but other structures were also deemed vulnerable in close vicinity of the ECRB: The EDC tendon, the joint capsule, and tendinous slip of the supinator muscle. Due to the various interconnections in close proximity to each other, it is not uniformly accepted that the underneath side of the ECRB uniquely attributes to lateral elbow pain.[30,33,34] The complex anatomy shown in Figure 2, may explain some of the vulnerability of the tissues of the extensor complex.[35]

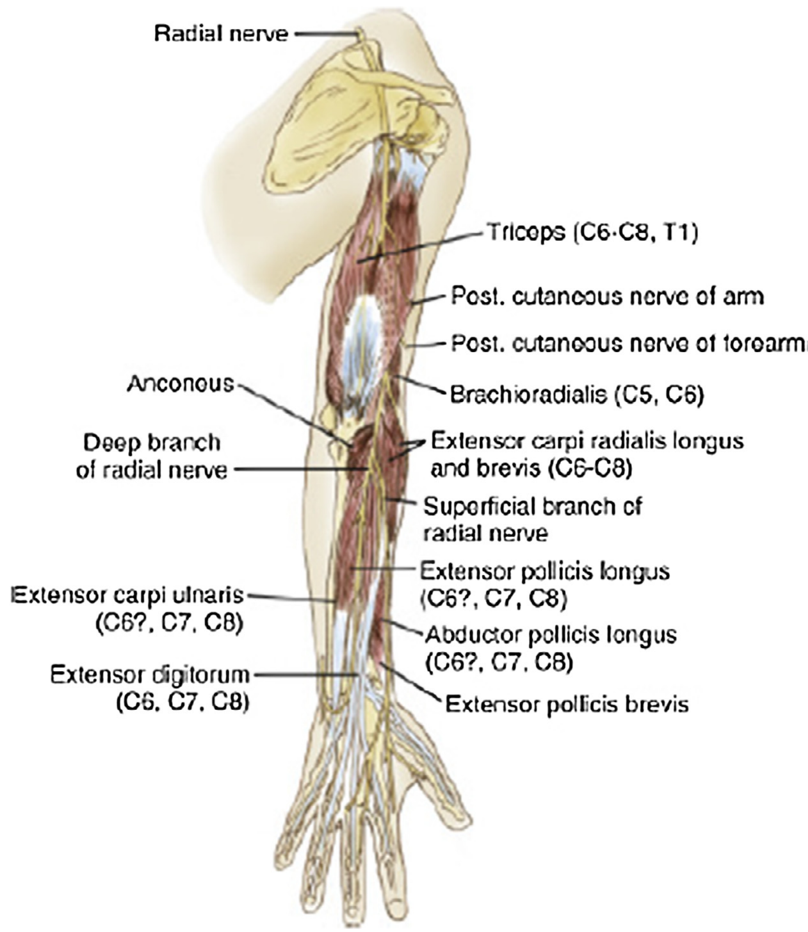


**Fig. 1.** The anatomical landscape. Morrey's The Elbow and Its Disorders. 2018 Chapter 2 Morrey, Bernard F.; Llusá-Pérez, Manuel; Ballesteros-Betancourt, José R.. Anatomy of the Elbow Joint. Pages 9-32 Figure 2.34 The right radial nerve and its innervated muscles.

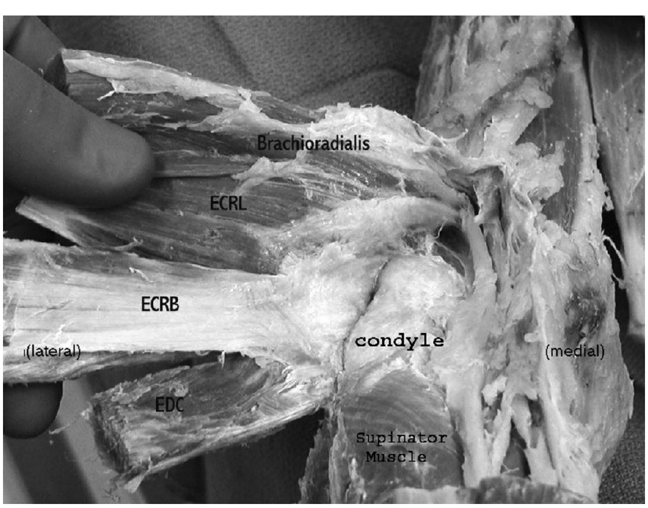


**Fig. 2.** From B. Bunata RE, Brown DS, Capelo R. Anatomic factors related to the cause of tennis elbow. J Bone Joint Surg Am. 2007;89:1955-1963. With permission. "The extensor mechanism could be reflected without separation of its components. All tendons were noted to blend into one fascial sheet at the elbow. This sheet slides against the capitellum during elbow motion, and the extensor carpi radialis brevis is in a vulnerable position within the sheet. ECRL = extensor carpi radialis longus, ECRB = extensor carpi radialis brevis, and EDC = extensor digitorum communis."

*Descriptions of the pathology*

Tendinosis of the lateral elbow belongs to the great family of tendinosis ailments.[14,36-38] Several review articles comment on the misnomer of "tennis elbow," because the prevalence of LE in tennis players contributes to only 5% of all LE cases.[39,40] What started as a functional description of "writer's cramp"[41] changed to "lawn tennis arm"[42] and progressed through time to increasingly finer descriptions of the tissue pathology, including lateral epicondylitis, lateral epicondylosis, lateral elbow tendinopathy, and currently extended not only to the tendon, but also to the enthesis, the transition between tendon and bony attachment, enthesopathy of the ECRB, so called eECRB.[34,43-46] Histological studies have substantiated the contribution of chemical reactive substances to explain pain perceived by patients with LE.[40,47,48] Alfredson[48] found elevated levels of neuro-glutamate in patients with LE, but no evidence of active inflammation. Intraoperative observations show the degenerative tendon disruption of the pathology,[49] and Figure 3 shows imaging results of the extended pathology reaching the collateral ligament and the enthesis of the lateral epicondyle.[50] Neurosensory contributions to the ailment are recognized. [46,51-53] The contribution of the scleraxis gene to the formation of force-transmitting tendons, including the dorsal extensor tendons of the forelimb was experimentally shown on a molecular level in mice.[54]

The etiology of LE is most often considered to be a repetitive-motion injury, based on findings in population studies. But it is only recently that, in cyclic loading laboratory studies, using a rat model of repeated grasping, that tendinosis of the flexor tendons

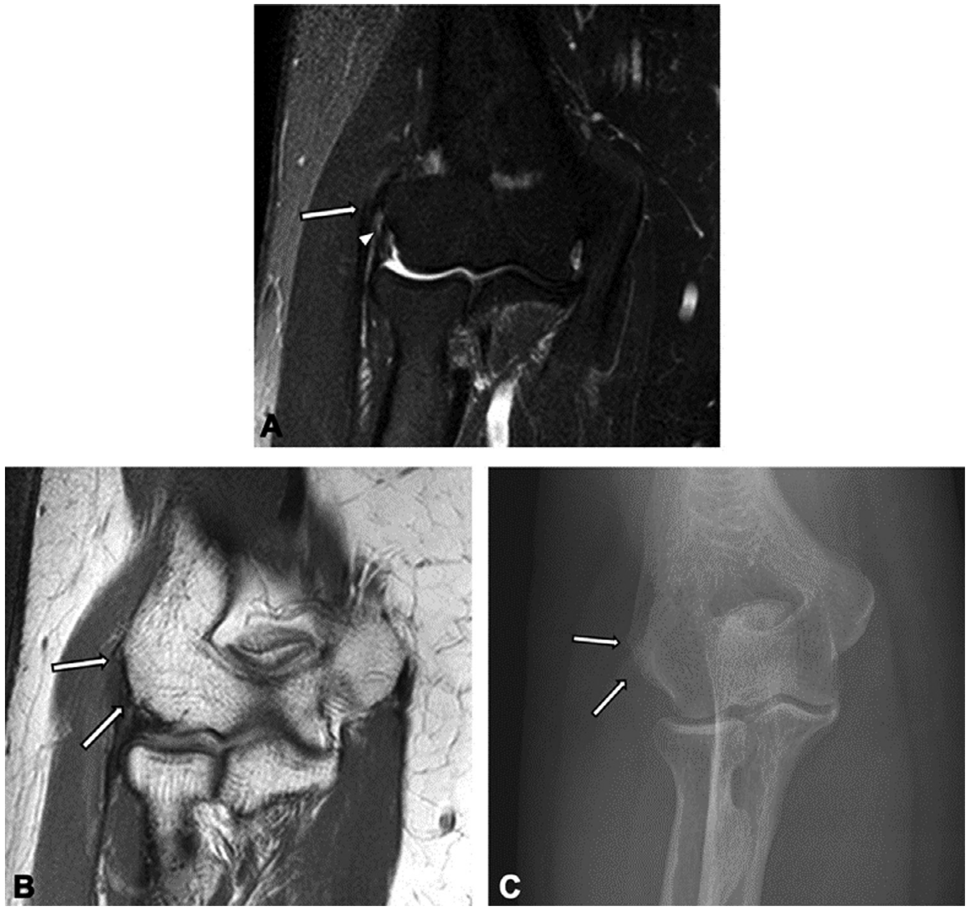


**Fig. 3.** Pathology. A 60-year-old female with right elbow pain for 5 weeks. (A) Coronal fat-suppressed FSE T2-weighted image showing mild thickening of the proximal portion of the common extensor tendon with increased signal intensity (arrow), suggesting mild injury. Irregular thickening with increased signal intensity in the proximal portion of the lateral collateral ligament (arrowhead) is also noted, suggesting mild injury. (B) and (C) Coronal PD FSE image and oblique radiograph showing cortical irregularity of the lateral epicondyle (arrows), a finding suggestive of enthesophytes. From: Cha YK, Kim S, Park NH, Kim JY, Kim JH, Park JY. Magnetic resonance imaging of patients with lateral epicondylitis: Relationship between pain and severity of imaging features in elbow joints. Acta Orthopaedica et Tramatologica Turcica. 2019;53:366-371

could be provoked and used to explain the repetitive nature of tendinosis.[36,55-57]

Table 1, presented in the appendix, lists prominent studies regarding the pathology and etiology of LE. The seminal observations and laboratory studies by Goldie[58] on the histopathology of LE have influenced thinking well beyond its original publication. Goldie compared the tendinous, vascular, and neurological configurations of intraoperatively obtained tissues from patients with LE to cadaver tissues of persons who had willed their tissues for research and who had reported no lifetime elbow pain upon impending death. Intraoperatively, tissues were collected from the ECRB and adjacent structures. Pathological tissue changes were observed at the underside of the ECRB where it rubs over an aponeurosis. Goldie concluded that the sub-tendinous tissue plays a bigger role than the adjacent aponeurosis and could be harmed by muscular contractions. Hypervascularity of the ECRB tendon was observed and considered to be a sign of attempted tissue healing. Goldie[58] observed an increase in free nerve endings to explain pain reported by patients, and unencapsulated nerve endings to explain pain upon pressure and vibration.

Current investigations have built on earlier findings by using novel imaging techniques and have further described the nature and extent of the pathological involvement of the tendons in patients with LE. Connell et al.,[31] comparing surgically removed tissues and preoperative ultrasound images of patients with LE to images on the uninvolved side, found fibroblastic degeneration, partial tears, and foci of calcification in the involved sides only. Involvement was most frequently found in the deep parts of the ECRB and the common extensor digitorum tendon (EDC) adjacent to the bone, more so than in the mid-section. Cortical irregularity and spur formation were observed in the adjacent bony structures. The lateral ulnar collateral ligament was clearly distinguished from the common extensor tendon and was affected in eight of 72 subjects (11%). The radial and posterior interosseus nerve were normal in appearance according to the study by Connell et al. [31] Chourasia et al.[34] using ultrasound and magnetic resonance imaging (MRI)-guided examinations of 26 patients with LE also observed characteristics of tendon degeneration in affected common extensor tendon: the presence of intra-tendinous calcification, tendon thickening, adjacent bone irregularity, focal hypoechoic regions, and diffuse heterogeneity of the affected tendon. Coombes et al.[46] summarized the pathology to include increased cellularity, an accumulation of ground substance, collagen disorganization, and neovascular ingrowth in the lateral elbow complex, primarily affecting the ECRB, but also the EDC and the lateral ulnar collateral ligament. Bachta et al.[59] observed tears in the common extensor tendon in 58 patients with chronic LE. Ljung et al.,[60] using light microscopy analysis of biopsies taken during surgery and from 20 patients and 5 healthy volunteers, found differences in muscle fiber type distribution between chronic LE patients and controls, showing a shift in the patient group from type IIB and IIAB fibers to the more oxidative type IIA fibers, possibly as a result of ischemia.

Recently, investigations have studied the transitional region between tendon and the bony attachment site, the enthesis, a structure frequently researched in the field of arthritis,[43] leading to suggestions to rename advanced tennis elbow to enthesopathy of the ECRB (eECRB).[45] Most recently, Cha et al.[50] retrospectively studied MRI recordings taken preoperatively from patients not treated with steroid injections, confirming involvement of ECRB and EDC tendons. In addition, associated elbow joint abnormalities were observed in 41 of 51 patients, including the medial and lateral ulnar collateral ligaments (80.4%), enthesophyte or calcification (25.5%), and intramuscular edema was found in the anconeus (1%), and common wrist flexor and extensor muscles (5.9%). Extensor tendon findings positively correlated with injuries to the collateral ligaments. Three radiologists read the images, and their interobserver agreement was high (ICC 0.898, 95% CI). Clinical guidelines for examination of the elbow apply these basic science and imaging findings in their diagnostic strategy.[61]

Ongoing studies recognize the importance of peripheral as well as central nervous system contribution to the symptoms experienced by the person with LE.[21,46] Innervation of the lateral elbow region is attributed to branches of the radial nerve innervating the posterior aspect of the periosteum of the lateral epicondyle, and to branches of the posterior cutaneous antebrachial nerve innervating the fascia, underlying fat, aponeurosis of the forearm extensors, radial collateral ligament, and the tip of the epicondyle. Subsequently, assessments have expanded to include testing of neurological systems. Quantitative peripheral sensory testing, such as threshold with monofilaments, tuning fork vibration, pain pressure points, and temperature perceptions may be used quantify neurosensory contributions to the ailment,[52,53,62,63] however, it is not yet clear how and to what extent outcomes of these quantitative measures reflect severity of LE.[52,62]

Central nervous system contribution was suggested when bilateral motor deficits were observed in patients,[21,57] and patients with LE were found to be less proficient in dexterity compared to uninvolved subjects.[51,64] Unyo[65] noted a shift in the flexor-extensor muscle balance in patients with LE. Recreational tennis players with LE did not only show decreased wrist extensor strength in comparison to subjects without LE, they also demonstrated decreased strength in the lower trapezius muscle.[66] Further investigation confirmed lower strength and endurance in the anterior serratus and middle trapezius muscles.[67] It is not known if pre-existing proximal weakness is contributing to the onset of distal elbow problems, or if the sustained presence of LE contributes to long-lasting shoulder muscle weakness. Heales et al.[68] confirmed differences in neuromuscular control between those with and without LE, suggesting differences in central control, however, further research was needed.

Based on the findings of LE pathology, several models of tendinopathy have been offered. Coombes[46] introduced model of lateral epicondylalgia integrating tendon pathology, motor system impairments and pain system changes. Fu[69] presents a linear theory of three stages: stage I of injury, stage II of failed healing, and stage III with pathological and clinical presentations. Cook et al.,[37] recognizing the variety in clinical presentations tendinopathy, developed a continuum model of tendinopathy that includes different pathways for exacerbating or healing of tendinopathy (Fig 4). The continuum is based on a relationship between tendon structure, tendon function and pain, and ranges from a non-painful tendon with low functional capacity to painful degenerative tendons, some with a healing reaction surrounding them. Macroscopic and microscopic observations in patients corroborate this theoretical model. The authors recommended adjusting treatment to the stage and severity of the damage and the stage and potential for healing. This could include strengthening of tendinous structures in an unconditioned person to meet the demands of a tasks, or advising a period of refraining from painful activities for patients with tendinopathy, including patients with LE. Magnusson and Kjaer[14] propose a similar model that includes the impact of inactivity, exercise/ training and injury on cellular and molecular changes in the human tendons, but also the impact of aging.

Animal studies corroborate the theory that LE is an injury of a repetitive nature. During high-exposure experiments using front paws finger and wrist flexor tendons in a rat model, degenerative changes were provoked in tendon, cartilage, and bone, combined with sensory and grip strength changes.[36,55-57] Performance of moderate-level tasks induced bone adaptation and a suggestion of muscle adaptation in another rat model study.[56] Most important and clinically relevant is the evidence from the rat model showing that bone damage after high-exposure repetitive grasping (multiplying reach rate, duration, grasp force, and grasp time) was reversed when exposure was reduced, leading to the suggestion that altering painful activities and motions may reverse tendinosis as well.[70]

*Staging of severity and models of disease recovery or progression*

Determination of the level and severity of pathology are important to guide rehabilitative and surgical decision making.[21] The ability to classify the stage of recovery, disease progression or regression is still developing and relies on various types of examinations and measures.

Physical examinations and patient reports are important links to diagnose and stage the chronicity and severity of LE. Nirschl[49] advocates for grading the severity of LE on a seven-point scale (from 0 to 6), rating pain and sense of stiffness in relation to one's ability to participate in daily activities or sports. A recently developed scale using pain with function and pain with palpation was proposed as an indicator of severity for rehabilitation purposes.[71] This severity classification is based on a general pain rating and the presence of pain with wrist extension, grip strength with a flexed and then extended elbow, and during palpation of the lateral epicondyle. The widely used and validated patient-reported scale, the Patient-Rated Tennis Elbow Evaluation (PRTEE) includes pain, pain with specific activities, and subsequent disability.[72]

Advanced imaging technologies, such as MRI and ultrasound imaging, are confirming and expanding the nature of LE, description of the condition, and the staging of severity of LE.[31,34,50,52,59,73,74] No consensus for a standard imaging protocol was found. But a four-point MRI scale is advocated for clinical use, based on signal intensity and cross-sectional area involved. The scale ranges from Grade 0 (normal tendon appearance) to Grade 4 (common extensor tendinopathy comprising more than 50% of the total cross-sectional diameter of the tendon).[34] An ultrasound image analysis score, developed by Maxwell,[73] rates tendon characteristics and hypervascularity of the tendon. The tendon characteristics scale includes measurement of tendon thickness (in millimeters), the presence of anechoic clefts or foci (intrasubstance tears), abnormal hypoechoic areas (collagen degeneration), intra-tendinous calcification, and cortical irregularity at the tendon insertion. Echogenicity was graded from Grade 0 (normal fibrillar echo-structure) to Grade III (severe inhomogeneous echo-structure). The grading scale for neovascularity ranges from Grade 0 "no neovascularity" to Grade III "severe neovascularity," with more than four vessels extending into the tendon.

Imaging examinations provide insight and understanding, but the structural image does not tell the entire story of the pathology or the recovery. Symptom-free persons without complaints of LE may demonstrate similar structural changes as patients with LE.[74]

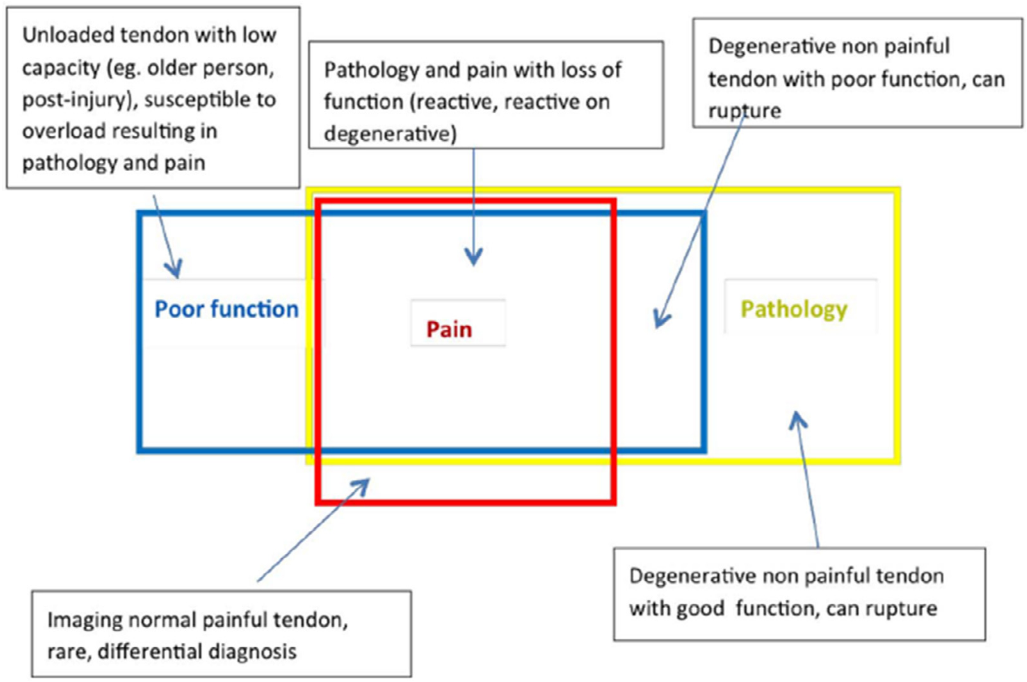


**Fig. 4.** Relationship between structure, function and pain. From Cook JL, Rio E, Purdam CR, SI Docking. Revisiting the continuum model of tendon pathology: what is the merit in clinical practice and research? Br J Sports Med 2016;50:1187-1191

A retrospective chart review of MRI imaging records of the elbows of patients without complaints of LE showed degenerative changes that mimicked changes observed in symptomatic patients in 11% of the subjects. Prevalence was higher for patients older than 71 years of age. Imaging results may also not be sensitive to express progress. Two studies reported that MRI imaging did not reflect the progress as quantified using pain scores, wrist extension strength, grip strength, and the PRTEE.[34,75,76]

*Tissue-level interventions*

Our brief synopsis of tissue-level interventions is limited to systematic investigations and randomized controlled studies from 2000 to 2021. The aim of this section is to present evidence of the mechanisms of these interventions to directly address the pathology in the context of Cook's model of continuum of tendinopathy.[37]

Proof of principle studies of interventions directly interacting with the involved tissues aim to enhance healing of the degenerative LE tissues by various cellular mechanisms, such as promoting protein synthesis within the fibroblast cells[76-78], managing vascularity,[78,79,80] transforming collagen structure,[81] changing gamma motor tone of muscle,[82] better aligning connective tissue fibrils,[7783,84] modulating nociceptive impulses, [85] enhancing extracellular matrix modification, [87] and neuromodulation.[78] Other treatments aim to unload involved tissues, such as altering the line of force production applied to the tendinous structure, or reducing force production or resting involved tissues by partial or full immobilization. Eight systematic reviews were found for commonly used modalities to treat patients with LE, including therapeutic ultrasound, transcutaneous electrical nerve stimulation (TENS), extracorporeal shock wave therapy (ESWT), low-level laser therapy, targeted exercises, dry needling, myofascial release, friction massage, acupuncture, counterforce braces, and wrist orthoses.

Rather than measuring cellular responses, clinical outcome studies use patient responses such as pain, grip strength, function or the Patient-Rated Tennis Elbow Evaluation (PRTEE) as outcome measures, and may thus reflect the load capacity of the tendon. An extensive review of 20 randomized trials and two systematics reviews, published by Dingemanse et al. (insert new reference), focused on various electrophysical modalities; pulsed electromagnetic field therapy, laser, TENS, electrical stimulations, and extracorporeal shock wave therapy.[206] A variety of control treatments was used, including bracing, exercise, plyometric exercise, acupuncture, chiropractic intervention, and platelet injections. Moderate evidence was found to support the use of ultrasound and ultrasound plus friction massage for improving pain and for laser therapy to improve pain and grip strength. Limited evidence suggests using electrical stimulation over the use of platelet injections to tender points for lessening pain and increasing grip strength and function; TENS applied to acupuncture points may also improve pain. Evidence existed for improving function and grip strength when using ultrasound, laser therapy, or electric shock wave therapy. One systematic review of the application of acupuncture showed significant improvements in pain scores in patients with LE, as compared to sham acupuncture, pain blocking injections and pain medication.[79] Dry needling involving repeated fenestration of degenerated tissue[80], showed low to moderate evidence supporting the use of dry needling to improve pain, function, painful palpation, sensitivity, and grip strength in patients with LE.[81] Laimi et al.[82] found that myofascial release improved pain and function after 2 months of treatment for patients with LE. The results of support for deep friction massage were conflicting; with one study not showing improvements in pain, grip strength or function,[83] while the other showed improvement in pain, grip strength, and functional scores at 6 months when compared to use of a wrist orthosis and corticosteroid injections.[84]

Various types of interventions are used to alter or lessen the load on impacted tissues. The benefit of unloading or alteration of the area of loading is based on the hypothesis that loading of a painful tendon perpetuates nociceptive stimuli, and that the secondary hyperalgesia in tendinopathy is a response to ongoing nociception.[38] Counterforce bracing has been shown to alter force transmission to the tendons at the lateral epicondyle and an increased threshold for provocative testing for pain during passive stretch to the wrist extensors was found after its use.[84] Conversely, in a recent systematic review of 16 randomized controlled trials, the effect of counterforce bracing to improve pain and grip strength in those with LE did not appear to exceed those of other interventions, such as the broad spectrum of physical therapy interventions, wrist orthoses, and laser therapy.[85] No reviews were found for the effectiveness of the application of taping to the lateral elbow, but the technique was noted in review papers.[21,86]

Wrist- and forearm-based orthoses may be used to limit extensor muscle force production, shorten the arc of muscle pull, and decrease force load of the tendons involved in LE.[87,95] Heales et al.[88] summarized that the use of orthoses significantly improved grip strength in patients with LE but did not significantly reduce pain. No consensus was found on the orthotic design of the applied wrist orthoses. Bazancir et al.[89] in a study of the sarcomere length as a contributing factor to LE, hypothesized and cautioned that repeated placing of the ECRB in an elongated position may lead to stretching of its sarcomeres, causing poor vascular supply. Thus, their orthotic design included both an extended wrist and a flexed elbow as a novel approach of immobilizing the muscle sarcomeres in a shortened position, to be worn for 1 week, followed by a carefully crafted graded mobilization program.[89] This should be reference number 89 Further research was needed to confirm efficacy of the approach.

Studies of locally targeted exercises vary in type and protocols, and address different sections of Cook's continuum model, such as aiming to reduce pain, or aiming to enhance load capacity and function of affected tendons. Reviews indicated that exercises may improve pain, grip strength, and functional outcomes in patients with LE.[90-92] Eccentric exercise protocols showed improvement in pain and function, although further research is needed to establish long term effects.[91,93] Moderate evidence supported stretching and strengthening exercises to improve pain, or cervical and thoracic manipulation combined with concentric, eccentric, and wrist mobilization exercises to improve grip strength outcomes.[94]

Clinical practice guideline development may be needed to formulate consensus about the most effective direct tissues targeted treatments used by occupational and physical therapists. The complex biomechanics and physiology of LE, and the range of stages that a patient may present with, makes it difficult to establish a universal, or "one size fits all" treatment method.[21] The patient may present in various stages of tendinosis that may impact lateral tissues, not only to the tendon, but also to the enthesis.[34,43-46] Neurosensory contributions to the ailment may be present,[21,51,52] but sensory changes were typically not yet addressed in tissue specific treatments in the reviewed studies.

The degenerative pathology may occur within a context of cellular responses indicative of attempting to heal. The feasibility to reverse pathology using watchful waiting, combined with refraining from painful activities, was shown in animal research on a cellular level.[70] Future studies are needed that contrast using the various tissue level interventions against using watchful waiting and refraining from painful activities in various stages of structural damage, pain or capacity for tendon loading for patients with LE.

### *Biomechanical findings, population findings, and ergonomic interventions*

#### *Biomechanical findings, tissue-based analysis of hazardous motions*

The primary objective of this study is to connect not only pathological findings but most importantly connect tendon and muscle biomechanics with ergonomic risk assessments and ergonomic interventions. Understanding anatomical and biomechanical principles of muscle and tendon behaviors are key to understanding the type of movements that may place persons at risk for the development or recurrence of LE.[38]

The function of a tendon is to transfer the tensile forces produced by the muscle action to the appropriate elements of the musculoskeletal system. The amount of load applied to the tendon depends on passive stretch and active force production by the muscle, expressed in standardized parameters. Strain is the passive elongation, expressed as a percentage of its resting length. Stress is the load placed upon the tendon. Stress is generally higher when loads are applied rapidly. The tendon not only transfers force but also has stress- and shock-absorption capacities because of its complex visco-elastic, dampening behavior.[38,95-97] But tendons are vulnerable. Of the highest clinical and ergonomic relevance is that tendons may undergo perpendicular compression by overlying tissues and shearing when they move around bony prominences. The magnitude of the shearing force is related to the magnitude of the compressive force and the speed of the motion.[38,98] Tendon tissues store elastic energy when stretched, exemplifies in the Achilles tendon, where the stored energy enhances the start of a jump.[15,99,100] No studies were found that investigated energy-storing capabilities of the ECRB and ECRL. The viscoelastic, buffer-like mechanical behavior of tendons lessens with aging.[14,101]

Muscle force production to provide stress to the tendon is mediated by the muscle architecture[102,103] and the type and velocity of contraction. Individual muscles are intrinsically designed for specific functions, and their design determines the quantity and quality of force production onto the tendinous structures.[102,103] Generally, with low velocity, the muscle can resist or generate more force; with high velocity, it can resist or generate less force. The type of contraction impacts the magnitude of the force, with eccentric contraction asserting higher forces than concentric contraction, and theorized to be a risk factor.[98] Active and passive load application by the tendon stress and muscle forces interact with the highest load on the tendon occurring when a muscle contraction is added to a maximally elongated tendon, depicted in the so-called Blix curve.[95] Recovery time between contractions is crucial to allow a full recovery to the resting position, impacting its interaction with passive visco-elastic components of the muscle.

#### *Vulnerability of lateral elbow tendons based on ECRB and ECRL muscle function*

Table 2 in the appendix shows studies of muscle and tendon composition and biomechanics of the ECRL and ECRB that are key for understanding tendon vulnerability during activities**.** The ECRB has more force-generating potential with larger forces at higher velocities, but its short fibers do not allow for force production over such a large trajectory of motion as accomplished by the ECRL.[103] Most importantly, it was found that the ECRB can assert full and equal tension throughout all positions of the wrist. All its force capacity is applied to wrist extension only, because it does not contribute to elbow motion and is not affected by elbow position. Sarcomere lengthening during ulnar deviation was the same in the pronated or neutral forearm position.[207] Consequently, Brand[95] called the ECRB the "workhorse" of the wrist. This is in agreement with a more recent study using surface electromyography (EMG) measurements of healthy subjects, where high ECRB activity was found during simultaneous gripping and twisting with a stabilized wrist. Even moderate ECRB activity was found during both supination (26% - 43% of maximum voluntary electrical activity) and pronation torques (17% - 55% of maximum voluntary electrical activity).[104] For the ECRB, the position of least mechanical advantage is its fully stretched position, resulting from wrist flexion, and to a lesser extent, ulnar deviation. The proximal attachment of tendon of the ECRB is compressed onto the lateral epicondyle by the ECRL when the elbow is fully extended. The ECRB is the most vulnerable as compared to the ECRL based on its location and its continues force production.

The ECRL, with its longer fibers, allows force production over a larger trajectory of motion compared to the ECRB. The ECRL crosses both the elbow and wrist, so elbow position will affect force production, and its force is divided over two joints. The proximal attachment of the ECRL runs up to 4 cm-5 cm proximal to the epicondyle along the lateral supracondylar ridge, allowing the ECRL's contribution for wrist extension even when the elbow is in full extension. The line of pull of the ECRL is suitable for radial deviation of the wrist, more so than the line of pull of the ECRB. For the ECRL, the position of least mechanical advantage is wrist flexion, wrist ulnar deviation, and elbow extension. The ECRL tendon is most superficial in anatomical location, not suffering from overlying compression or suffering from shearing due to closeness to bony prominences. The ECRL is the least vulnerable of the two, based on its location, and force production shared over two joints, resulting in non-continuous activations.

Lieber et al.[102] observed the benefits of the synergistic function of the ECRB and ECRL by studying sarcomere length changes intraoperatively in seven subjects moving the wrist passively through flexion and extension (with the elbow fixed at 20° flexion). It was concluded that the synergy of ECRL and ECRB muscles work can accomplish the same force and excursion as one muscle would, but with a combined muscle mass that is 30% smaller.

*Vulnerability of lateral elbow tendons based on muscle/tendon anatomy and kinesiology*

Multiple studies investigated the interplay between the active and passive forces placed on lateral elbow components to determine where excessive strain, compression and shearing, or muscle tension could explain tissue vulnerability and tissue damage observed in patients with LE.

*Elongation (strain).* Briggs and Elliott,[105] studied the anatomy of 139 cadaver limbs, in specific attachments of the ECRB and adjacent wrist extensor muscles, neural and vascular variations, and the impact of lengthening of the ECRB with position changes in the elbow, forearm, and wrist. The origin of the ECRB was described as a keel-shaped tendon. Pronation and supination impacted lengthening of the ECRB when combined with wrist position changes. Muscle lengthening was found to be most marked with the forearm in full pronation and the wrist in palmar-flexion and ulnar deviation.

*Compression and shearing.* In a study of 60 cadavers, Bunata et al.[35] observed the impingement and shearing of the ECRB between the condyle/epicondyle and the overlying and surrounding wrist extensors. The anatomical vicinity of adjacent tissues is shown in Figure 2. The fully tendinous composition of the ECRB insertion was found to lay deep—closest to the bony epicondyle and capitellum. It was most superiorly located within the tendinous insertions shared with the EDC and the ECU. The tendon of the ECRB was vulnerable to impingement (compression) because it was located adjacent to the capitellum and was covered directed by the EDC, and was additionally compressed by muscular sections of ECRL overlying the ECRB, EDC, and ECU components. When the elbow was flexed at 90°, a view of the ECRB and ECRL combined showed both structures free of the capitellum.

Two possible potential sources of abrasion were theorized by Bunata et al.[35] With increasing elbow extension, stretching of the ECRL was putting the underlying ECRB structure under increasing compression. Secondly, the ECRB itself was vulnerable to sideways shearing, when upon elbow extension, the ECRB stretched, bowed over the condyle, sliding laterally. An experimental placement of a suture from the capitellum to the second compartment at the wrist (the distal insertion of the ECRB) showed the cumulative abrasion through the lateral displacement of the tendon and rubbing of the ECRB against the capitellum and against the radial head in the final 30° of extension. Figure 2 shows the vulnerable underside of the extensor tendon complex.

*Compression and stress, ECRB, ECRL, and EDC.* In a cadaver study of eight fresh cadaver specimens Tanaka et al.[106] followed up on the studies by Bunata[35] to investigate contact pressure underneath the ECRL, ECRB, and EDC against the capitellum under four elbow flexion angles, three forearm rotation angles, and three weighted varus stress loads. With increasing load similar to increasing muscle tension, contact pressures against the capitellum were larger for the ECRB and ECRL compared to the EDC. The highest contact pressure was measured with the fully extended elbow in the pronated position. Critically important for ergonomic interventions is that a gradual decrease in contact pressure already started at 30° of flexion until the lowest at 90° of elbow flexion measured during the same simulated tension load, both in the pronated and neutral forearm position. A higher elbow varus load resulted in higher compression by tendons on the capitellum.

These findings of shearing, compression and stress form the basis for some of the well- known diagnostic tests. Diagnostic provocation of pain (upon palpation or spontaneous increased pain) is produced by either making the ECRB contract, stretch, or become compressed. Painful resistive active wrist extension with the flexed elbow may point to contribution by the ECRB, called the Cozen's test.[61,107] Passive wrist flexion combined with elbow extension and forearm pronation places the highest strain and compression on the ECRB tendon, the Mills' Test.[61,107] The resisted middle finger extension test places emphasis on the EDC contribution of the LE diagnosis, the Maudsley's test.[33,61] No studies were found to add resisted wrist extension to the already stretched out tendon in the Mills' that will maximize tension and compression in the tendon of the ECRB. Despite universal use of these diagnostic tests, further research is needed.[108]

*Vulnerability and relationships in the kinetic chain of motor control*

Elbow function does not occur in isolation, but occurs in the total kinetic chain of human motor control needed to accomplish daily tasks.[109] In turn, ailments impacting the elbow may be related to changes in the entire kinetic chain of movement, noted by Unyo[65] in the altered force ratio between wrist extensor and wrist flexors of 8 patients recovered from LE (clinically without symptoms) and 16 healthy control subjects. More proximal changes in the kinetic chain were observed as well. Recreational tennis players with LE did not only show decreased wrist extensor strength in comparison to subjects without LE, but they also demonstrated decreased strength in the lower trapezius muscle.[66] Further investigation confirmed lower strength in anterior serratus and middle trapezius strength and endurance as well.[67] It is not known if proximal weakness causes the distal problems or vice versa. Reports on sports injuries stress the importance of evaluating not only the site of pain in the athlete, but also the entire kinetic chain demonstrated by the athlete during the performance of the sports or when using various types of equipment,[12,110-113] Reversing changes in the kinetic chain has benefitted patients with LE, such as after inclusion of shoulder exercises.[114] A recommendation of timing and type of exercises, illustrated with clear pictures, was provided as a mode to affect the local and proximal dysfunction along the kinetic chain.[115]

*Population analysis and measurement of exposure hazards and ergonomic interventions*

*Exposure hazards: motions, activities and mediators*

Observations of populations can demonstrate which types of activities may expose a person to risks for developing LE; validating, disputing, or expanding biological explanations for triggering repetitive injuries. The literature review, summarized and listed in the appendix in Table 3, shows study designs, types and numbers of workers, exposure measurement and results. The numbers of workers in the observational studies ranged from 146 workers[116] to 9696 workers.[117] The studies with the lower numbers of subjects aimed to find specific correlations, such as Aben et al.[118] seeking to profile psychosocial characteristics of affected workers in specific populations and larger sample size studies including multiple occupations.[119-122]

*Types of exposures: Hazardous motions and activities*

The following exposures were noted to affect the upper limb in general in terms of applied forces: intense exertions, long-duration exertion, eccentric or lengthening contractions, and sudden or ballistic exertions (high velocity),[38] high angular velocities, friction and the force of muscular contractions, including static contractions,[116] lack of muscular rest, and non-neutral wrist positions. *Activity* focused hazardous activities for the upper limb general were: vibrations, use of gloves, localized compression, and coldness < 45° F.[123,124]

The following exposures were noted specific to LE in terms of applied forces: combining repeated forceful work in non-neutral postures of the hands and arms, higher percentage of time spent in supination > 45° or pronation > 45°, combining supination and forceful lifting, high wrist angular velocity, wrist flexion, repetitive bending and straightening of the elbow, reaching, eccentric contraction of wrist extensor muscles, combination high physical exertion and elbow flexion/extension, and extreme wrist bending, high grip forces. *Activity* focused hazardous exposures specific for LE were: handling of tools and loads in overhead positions, working with vibrating tools, and awkward upper limb postures. Also indicated were kinetic chain elements: poor seating, awkward postures, and non-ergonomic tool design.[7,22,117,125-137] Lastly, Walker-Bone and Cooper[138] observed the presences of combinations of force, repetition, vibration, and/or levels of psychological well-being to be associated with LE, but questioned whether exposure to mechanical factors initiate the disorder or aggravate a tendency among predisposed subjects.

*Personal and organizational mediators*

Personal factors, as well as contextual organizational factors, may play an important role in the onset, remediation or prevention of repetitive-motion injuries. The right upper extremity was more affected than the left.[139] Personal factors included; age between 36 and 50 years old, being female, and/or being a smoker.[127] Low social support increased the odds for LE, but a *protecting influence* was found for high social support. Workers with LE were found to have less work satisfaction compared to workers without LE. A difference in the type of personal factors was found between male and female subjects; men scored significantly higher on perfectionism, were more likely to develop an anxiety disorder or depression, and indicated a significantly higher workload compared to controls. Women with LE reported significantly lower job autonomy and less contact with colleagues compared to matched controls.[118] Thiese et al.[122], in a cross-sectional study of 1,824 participants found that the largest associations between LE and personal factors were always/often feeling physical and mental exhaustion after work.

Punnett[140] added organizational features of the work environment, such as time pressures and low decision latitude for workers to occupational ergonomic stressors. Bao et al.,[121] exploring work organization variables in 1,834 subjects, found that paid overtime work was associated with a lower prevalence of LE. Lack of job rotation was borderline associated with LE, and no significant relationships were detected between work pacing and the health outcome variables in their sample.[121] In a qualitative study of 11 patients with a variety of upper extremity repetitive motion-related diagnoses, King[141] confirmed these personal factors, such as strong work ethic, organizational factors, and the positive impact of family support but also found a negative impact of family conflict.

*Measurement and scoring of exposure*

Measurement of exposure to hazardous activities is important to assess risk and outcomes for individual patients and groups of workers alike. Data collections from workers include physical examinations, personal characteristics such as hand dominance and general health questionnaires, work related questionnaires, structured interviews, plant walk-throughs, work observation, video recordings at workstations, worker self-report of exposures, and social support scales. Moore[123] and Garg et al.[142] included the Borg Scale of Perceived Exertion to rate self-reported work intensity. Flexible electrogoniometers and surface EMG were used in one study applied to 761 male and 1891 female workers.[124]

The Hand Activity Level (HAL),[119,120] the Composite Strain Index (COSI), Cumulative Strain Index (CUSI), and Strain Index and Revised Strain Index[98,142-144] have been developed to determine a dosage of exposure, including the type of exertion hazard, the frequency, duration, and the pauses in hand activity within job cycles. The HAL scale, based on direct observation, is an ordinal scale with anchors progressing in steps of two allowing intermediate rating in steps of one.[119] The anchors include a combination of frequency of hand motions, steadiness of motions and the frequency of pauses. The examiner rates hand activities of the most active hand for at least five activity cycles and averages the count to determine the mean HAL score for the observed cycles. Reliability of the assessment tool was tested in a study of 352 workers. The reliability correlation between initial and ratings taken two years later (with the task being consistent) was good ( $r^2 = 0.88$), and paired tests show a significant difference that was 0.6 units within the one-unit criterium.[120] The quality of scoring with the HAL depends on the observational skill of the rater, but the scale is fairly easy to use and does not depend on intricate calculations. In contrast, complex calculations are needed for the Revised Strain Index, COSI, and CUSI.[143,144] Based on a data collection of video recordings, a system of algorithms and calculations links job demands and biomechanical stressors taking place during an entire task and its subtasks into a Strain Index score. The RSI is calculated for each subtask of a task, rank ordered, and computed into the COSI. The COSI of each task is then rank ordered and combined with the hours per day that the task is performed to compute the CUSI. Thus, the CUSI integrates the type and intensity of physical exposures during hand activities with other dosage elements of frequency and duration. Garg et al.[144] recommended proactive use of this system using the RSI for designing and analyzing tasks to determine the risk for repetitive musculoskeletal injuries. The system was independently validated in a study of 607 workers**.** Using individual job physical exposures and health outcome measures, the RSI can effectively identify jobs with increased risk of developing LE. A high exposure (RSI > 5), older age, and self-perceived poor general health were associated with incidence of LE.[133]

With the ability to quantify the dosage of exposure comes the opportunity to estimate a safe level of exposure. The American Conference of Governmental Industrial Hygienists (ACGIH), a worldwide organization known for measuring and establishing Threshold Limit Values (TLV) for chemical and biological exposures, also established health hazards associated with occupational exposures. The ACGIH recognizes hazard analysis as a major requirement for the effective management of upper extremity musculoskeletal disorders. TLV values were also investigated for the risk of LE.

In a systematic review of 13 articles, van Rijn et al.[22] found the following TLV values related to LE: handling tools > 1 kg, handling loads > 20 kg at least 10 times per day, high grip forces for > 1 hour per day, arm lifting or hand bending for more than 25% to 75% of working time, working with vibrating tools for > 2 hours per day, repetitive movements > 2 hours per day, low job control, or low social support. Walker-Bone et al.[117], in a study of 9696 workers, determined that LE was associated with manual work and repetitive bending and straightening of the elbow > 1 hour per day. Herquelot et al.,[131] in their study of 3710 workers, found that physical exertion perceived as hard combined with elbow flexion/extension and wrist bending for > 2 hours per day were strong risk factors for LE. Fan et al.[134], in their study of 733 workers found the following predictors of dominant-side LE: the combined effect of forearm pronation ≥ 45° for ≥ 40% of time, time spent in forceful exertion, including any power grip, upper extremity lifting for 3% of time, and forceful exertions for at least 10% of duty cycle.

While varying between study samples, TLV studies indicated that exposure between 1 and 2 hours per day of repetitive elbow flexion and extension, wrist bending, and forceful work may pose a risk for developing LE. Combinations of elbow motion, elbow pronation with wrist bending, or elbow motion with forceful activities, including gripping, are all mentioned as risk factors.

## *Ergonomic interventions: Background and evidence*

### *Ergonomic background and principles*

Understanding principles of ergonomics are key to understanding approaches and design processes, as well as research strategies to assess intervention outcomes. The field of ergonomics attempts to identify stressors to the human system to avoid them by proper design and recognizes the importance of contextual features that impact the kinetic chain of movement and control physical function as key components of design.[28] "Ergonomics is a discipline that is both a science and a technology that includes what is known and theorized about human behavior and biological characteristics that can be validly applied to the specification, design, evaluation, operation and maintenance of products and systems to enhance safe, effective, and satisfying use by individuals, groups, and organizations."[27,145,146]

Several types and processes of ergonomics exist. One of those is called participatory ergonomics because it considers the workers to be a crucial element for return-to-work interventions and for design prevention strategies. It is proposed as a most effective means of eliminating or redesigning manual tasks to reducing musculoskeletal disorders.[147] The field of participatory ergonomics makes a nice fit with the practices of hand therapists, occupational and physical therapists alike, by including the patient as a change agent important for success.

One key objective of ergonomic design is to organize and design activities so that joints and muscles are placed in a neutral position. A report of investigations published by the Centers for Disease Control and Prevention in 2011 combines work efficiency and worker safety when describing the benefits of designs that place the worker in neutral positions during activities.[148] "A neutral posture is achieved when the muscles are at their resting length and the joint is naturally aligned. In the neutral position, muscles can assert force most efficiently and with the least stress to involved joints and to force transferring tissues. It is postulated that when working in awkward, non-neutral positions, fatigue occurs sooner, and that working at extreme ranges of motion cause stress on muscles and joints."[148] The neutral position for the wrist is 0° of extension and midway between radial and ulnar deviation. Positioning of the wrist in neutral position during grip and pinch recommended for ease of work.[148] The neutral position for the elbow is listed at $90^0$ of flexion, and midway between pronation and supination, the neutral position for the shoulder is at the side of the trunk with slight abduction.[148]

The neutral positions match biomechanical and anatomical findings for the ECRB, ECRL, and EDC to lessen potentially hazardous exposure. While neutral positioning guidelines may not be intended to be applied rigidly, no guidance is given as to how far one could safely deviate from the position. Biomechanical and imaging information confirm that 90° elbow flexion eliminates compression of the ECRL on the ECRB. The evidence further suggests that starting at 30° of elbow flexion, many hazardous risks are beginning to lessen: compression of the ECRB between the contracting ECRL, the capitellum, and the dorsally moving radial head is beginning to lessen,[35] as well as lateral shearing of the ECRB over the capitellum.

### *Evidence for ergonomic interventions*

Ergonomic interventions may have similar aims to address similar constructs but may vary in their applications. No single exact method of adjustment may work for all situations,[149] nor will outcome of research be generalizable to all populations. The framework for behavioral intervention development by the National Institutes of Health provides a strategy to show the value of salient topics in ergonomic interventions for patients with LE. The stages for behavioral intervention development are: basic science (Stage 0); intervention generation, refinement, modification, adaptation and pilot testing (Stage I); traditional efficacy testing (Stage II); efficacy testing with real-world providers (Stage III); effectiveness research (Stage IV); and dissemination and implementation research (Stage V). Proof of principle studies were included in Stage 0 in this review. Table 4 in the appendix provides detailed study information on each of the stages of behavioral research development for patients with LE.

*Stage 0: Basic Science.* Stage 0 included "proof of principle" and "normative" studies. In an experimental office work setting, the optimum distance and direction of reaching in the office work setting to limit ECRB force production was tested in five healthy subjects. An arc ranging between perpendicular to the person to 30º to the side at a short distance produced the least ECRB activity.[150] The impact of office keyboard designs and person positioning (in a neutral standard position, using the keyboard placed on your lap, and using the keyboard in a reclining position) showed highest wrist extension EMG in the reclining position and confirmed that longer durations in one position increased discomfort for all positions.[151] Experimental testing of the impact of wearing gloves in 21 healthy subjects showed that using gloves increases fatigue in flexor digitorum muscles during resisted wrist isometric and eccentric contractions, as measured by EMG of the flexor digitorum superficialis.[152] Adding shock absorbing materials and other unspecified adjustments to a hammer handle resulted in decreased wrist extensor activity during hammering, as evidenced using 50 healthy subjects.[153] Experimental exploration of the feasibility of the application of a wrist orthosis to limit ECRB activity, studied in 13 healthy subjects, found that a wrist orthosis may not decrease

ECRB activity during common, or even light functional activities, such as lifting a folder.[154]

The feasibility of successful use of an educational module was shown in a study of 10 ophthalmology residents who were able to use information provided in an educational ergonomic module to successfully adjust eye examination work set-up to alter their body positioning in the kinetic chain of the neck, trunk, and shoulders, lessening elbow extension and, in some cases, pronation as well.[155]

Efficiency of racket handle size during standardized tennis strokes was studied in eight healthy males who were regular tennis players. Racket handle diameter, tested at 95, 105 and 115 millimeters diameters, affected hand force application and ECRL and ECRB muscle tension, with the most efficient size the median 105 millimeter diameter racket handle. [156] A summary article by Hennig[157] showed that stiffer tennis rackets and lower applied grip forces reduce the mechanical loads on the arm, without impeding ball velocity. Beginners were less efficient in hitting the ball and experienced substantially higher vibrations at the wrist as compared to experienced players.

Sardelli[158] studied functional, naturally occurring range of motion of the elbow during contemporary motions, such as the use of a cell phone and typing on a keyboard in 24 healthy subjects. The widest arc of elbow motion was for picking up a cell phone and putting it to one's ear (23° of elbow flexion to 130° of elbow flexion). The maximum pronation-supination arc was for using a fork (103°). Maximum pronation occurred when typing on a keyboard (65°), and maximum supination was noted with turning a doorknob (77°).

*Stage I: Intervention generation, refinement, modification, and adaptation pilot testing.* Stage I studies included two case reports of patients with LE showing the process of intervention generation [159,160] and two studies of groups of workers[125,161,162] showing refinement and pilot testing of multidisciplinary interventions, and raising awareness that studies of larger groups focus on the benefits to the upper limb rather than the elbow only.

The strength of the case report by Smith et al.[159] was that it showed how one employee's struggle with LE and equipment modification created a cascade of global workforce improvements. The ergonomic assessment of a single phlebotomist with LE led to leadership's awareness of a departmental problem, resulting in device alteration by the supplier to lessen pain when breaking needle seals, a task frequently performed as a phlebotomist. The patient experienced no recurrence of LE after the implementation of the ergonomic device, and the supplier altered the design for all users. McCormack[160] showed the benefit of using multifaceted ergonomics as a first line of intervention for a patient with LE. Ergonomic adjustments to the environment (lighting), the keyboard, adding a resistive mat to facilitate ease of moving the chair to adjust positioning, and education in neutral positioning of wrist and elbow, combined with behavioral changes in work pacing, resulted in a decrease in headaches, increased activity tolerance, and greater comfort at the patient's workstation. No measurements or pictures were presented of the altered positioning.

In a comprehensive longitudinal study conducted from 1980 through 1988 of a group of 695 workers performing assembly of electronic and small car parts, it was shown that after an interdisciplinary approach by engineering and health and safety professionals, the incidence rate of upper limb disorders was decreased, including the incidence rate for subjects with LE.[125] Harari et al.[162] reported that after implementing a 22-month multifaceted program provided by a physical therapist to logistics employees and office workers (N = 126), work productivity increased, and musculoskeletal pain and lost workdays decreased including the intensity and frequency of elbow pain. No changes in worker positioning were mentioned or depicted. Of note, the workers were not given the opportunity to participate on the design of the program.

*Stage II: Traditional efficacy testing.* Efficacy testing studies varied in design, purpose, and findings, and included interventions for the total upper limb. The evidence showed the problem of determining the most effective intervention when multifaceted interventions are simultaneously applied. The evidence brought to light the great variation in ergonomic interventions.

Sundstrup et al.[163] published a well-defined randomized study protocol for 66 slaughterhouse workers with chronic pain, including patients with LE, that contrasted exercise versus ergonomic interventions. The authors showed clear pictures of the exercises and a defined progression strategy, including instructions for workers to stop exercises if pain increased. The exercises used handheld weights and resistive bands in the extended elbow position to provide resistance for shoulder exercises. The study, now completed,[164] showed that this carefully guided strengthening program resulted in better outcomes to reduce LE pain, improve DASH scores for the shoulder, elbow, hand, and wrist and resulted in better workers perceived improvements as compared to the outcomes of ergonomic interventions. Soler-Font[165] contrasted effects of a multifaceted phased program consisting of participatory ergonomics, Nordic walking, healthy diet instructions, mindfulness, and a case management program for nursing staff (N = 246) against a control group receiving customary occupational therapy (N = 133) and found a greater decrease in musculoskeletal pain, including a decrease in elbow pain in the multifaceted intervention group versus the control group.

*Stage III: Efficacy testing with real-world providers.* Efficacy testing studies showed differences in study approach, interventions, measurements, and reported outcomes in real-world applied studies.

A randomized double-blinded study of 103 patients compared applied treatments and outcomes of a structured multifaceted program provided by a physical therapist in one facility with 194 subjects treated in the community. Outcomes using the Patient Rated Forearm Evaluation Questionnaire were collected via mail. The structured program included a home exercise program, night bandage, and wrist support. In the community, the primary focus was on the use of corticosteroids or NSAIDS for reducing pain and recurrence. After 2 years, patients in the structured program had less pain and functional loss, fewer recurrences, and less sick leave compared to the control group.[166]

The frequency, depth, scope, and type of face-to-face interaction during ergonomic intervention may impact results. Haahr et al.[126] reported that a minimal ergonomic program, an educational pamphlet, did not benefit subjects in a randomized, unblinded trial, that used outcome measurements applied by independent data collection. Subjects in the ergonomics group were referred to an ergonomics professional, but this professional was not instructed to include an ergonomics intervention but, instead, included instructions on graded exercises.

*Stage IV: Effectiveness research.* A systematic review by Sundstrup et al.[149] concluded that not enough evidence was presented to substantiate the benefits of ergonomic interventions for high physical-demand occupations, because scenarios were so varied, especially with participatory interventions. A systematic review of ergonomics in violin and piano playing similarly noted inconsistency and low quality of ergonomic measurement.[167] Heidarimoghadam et al.[168] called for clear definitions of interventions and study methods to test the efficacy of ergonomic programs on outcomes of workers with musculoskeletal disorders, including outcomes of productivity.

*Stage V: Dissemination and implementation research.* Stated with caution, no studies were found that investigated dissemination strategies and or service delivery aspects, but two examples illustrate how a process of change can be organized.

Koningsveld[169] listed a process of eight steps to generate and implement change, that was successful when applied a variety of workers, including construction workers, long distance drivers, and home care providers. The components of the process were: (1) inventory of problems, (2) worker participation, (3) management support, (4) step-by-step approach, (5) expand focus beyond health issues, (6) establish steering group, (7) check program effects, and (8) check the cost/benefit ratio. Koningsveld cautioned against poorly defined and implemented ergonomics. Gyi[170] reported promising results of their process of implementing an ergonomics program at 17 companies, each employing more than 500 transportation drivers. The process consisted of initial meetings (face-to-face with email and phone support), co-development of interventions, train the trainer sessions, implementation of interventions, pre and post-test questionnaires, interviews, and final meetings. Workers reported that they used the car as an office, doing computer work with the keyboard on their lap, using cell phones, and eating lunch. Communication of available resources was a problem, as only a few drivers were aware of the availability of the "train the trainer" educational module. Driver turnover was high and limited the conduct of the repeated testing before and after interventions.

*Integration of results.* Table 5 shows a theoretical integration of review results linking biomechanical and population exposure findings into ergonomic parameter suggestions, where possible with ergonomic examples.

## Discussion

The goal of this literature review was to build bridges, connecting pathological lateral elbow structures and wrist extensor function with activities, participation in life roles, environmental factors, and personal contexts in management of tennis elbow. The format of the review, an integrative review, was used to present the status of science for each study component and integrate the components into a theoretical framework. An integrative review stands out from other reviews, in that it may summarize past empirical and theoretical literature of all levels of evidence to enhance comprehensive understanding of a problem.[171] And indeed, all such types of literature were needed to integrate the understanding of LE and its treatments.

The framework of the International Classification of Functioning, Disability and Health (ICF) provided by the World Health Organization was of great use in organizing the methods of the review. Models of thinking about the pathology vary from models of progressively failed healing[69] to Cook's model of a pathology continuum, an interactive model ranging from uninjured tendon tissues more or less well-trained to degenerated tissues in the context of tissue healing, depicted in Figure 4.[37] After review of the pathology, the term lateral epicondylosis was selected for this article in appreciation of LE among the wider arena of tendinosis ailments.

The mechanisms of various tissue based intervention were confirmed on a cellular basis, and clinical studies showed benefits to lessen pain, improve grip strength and function. Except for exercise protocols, no mention was found for using the models proposed by Cook et al.[37] and Coombes[21] to tailor tissue based interventions to the stage and severity of the disease, or to the model by Fu et al.[69] to treatment with a theoretical stage of failed healing.

Various measures and imaging techniques are used to diagnose and rate the severity of LE or to present outcomes of rehabilitative interventions, from patient-reported visual analog scales of pain at rest and during activity to MRI imaging techniques, but none will suffice by itself. Outcome measures include grip strength with flexed and extended elbows, and various patient-centered scales exist that combine elements of pain and function. One study, conducted in healthy subjects, suggests the feasibility of using MRI as a tool to study ECRB and ECRL activation during a variety of tasks in patients.[172] Our findings add face validity to the PRTEE questionnaire by confirming hazardous exposure included in the questionnaire: repeated arm movements; carrying objects (in the PRTEE, a grocery bag or briefcase); and activities that involve forearm rotation and wrist extension, such as turning a doorknob or key, opening a jar, or wringing out a washcloth or wet towel.[72] This review supports the use of a battery of structural, functional and patient perceived measures to complement each other, because measuring the subject's pain level does not provide information about structural recovery, and the structurally weakened tendons observed via MRI may not be specific for patients with LE, because it may also occur with advancing age in persons without LE.[74]

Further research is needed into the role and focus of localized and full kinetic chain exercises. Weakness affecting the entire kinetic chain of movement was observed in patients, and inclusion of shoulder exercises has benefitted patients with LE in the clinical[138] and workplace setting.[163,164] Although eccentric exercises directly targeted to the wrist extensors are preferred at this time, more research is needed into the long-term results.[173] The model provided by Cook[37] may be helpful in targeting exercises to pathology stage, because evidence from a small sample study of high-intensity training used exposure to at-risk motions to retrain athletes to perform these motions against resistance after the painful episode had subsided.[111,208]

Population findings identified a multitude of activities associated with LE, including heavy lifting, reaching, work in awkward hand positions, use of heavy tools, use of gloves, precision hand activity, frequent handling of loads, use of vibrating tools, and high-impact activities as potentially harmful. Exposure hazards observed in populations theoretically matched with biomechanical hazard information of muscle and tendon function derived from cadavers, intraoperative observations, experimental studies of muscle activation, and more currently from imaging studies. None contradicted each other, but no biomechanical studies were found examining the harming effects of vibrating tools on the wrist extensor tendons.

Lateral epicondylosis continues to be considered a problem that significantly hinders participation in life roles even when many cases resolves on their own, [45,174] without the application of formalized medical or rehabilitative treatments. No studies were found that investigate whether persons with LE seek and find motions adaptions on their own to allow this spontaneous healing.

Based on the review of biomechanics and population, the following recommendations may assist therapists' symptomatic patients in decreasing harmful motions or activities for patients with LE: (1) force: reduce excessive, ballistic, or high-velocity force, high eccentric contractions, or wrist extension force applied to the fully elongated muscle; (2) compression: avoid the final 30° of elbow extension combined with full forearm pronation and wrist flexion to reduce compression of the ECRB (ECRL compression on one side the ECRB and the dorsal movement of radial head from the other side); (3) shearing: a) relieve proximal sideways shearing of ECRB over the capitellum by avoiding repeated final $30^0$ degrees of elbow extension, and b) relieve longitudinal shearing during wrist flexion and extension by avoiding this motion with the elbow in the final $30^0$ of extension, that would simultaneously compress the ECRB. The neutral, safe position of the elbow still is $90^0$ of flexion, but the safe zone may be wider ranging from $30^0$ to $90^0$

**Table 5**
Recommendations based on integrating biomechanics, population findings, and ergonomics to minimize forceful loading, compression, and shearing of lateral elbow tissues

| Muscle contraction: force, speed, type of contraction | | |
|---|---|---|
| Biomechanical risk findings: Body function | Population risk findings: Activities | Integrated considerations to alter body functions during activities to protect elbow tissue structures |
| The extensor carpi radialis brevis (ECRB), the “workhorse of the wrist,” may never rest during repeated wrist activities, possibly having insufficient recovery time for tendinous structures under high-velocity repetitive activities. | Forceful exertions combined with forceful lifting, high force activities in combination with forceful forearm pronation and supination and power grip<br>High rapid rate of force development, high wrist angular velocity<br>Ballistic motions involving maximum velocities and accelerations over a very short period | • Lessen speed of a lift.<br>• Eliminate 1 or 2 of the elements of the lift.<br>• Lift in supination.<br>• Allow design changes to lessen the trajectory and weight of the lift.<br>• Allow worker latitude to vary the lift and speed.<br>• Lessen speed of or need for ballistic motions.<br>• Assess for the need for ergonomically designed tools to offload forces, such as by increasing lever arm of the tool.<br>• Alter kinetic chain to divide speed and acceleration over legs, trunk and arms. For instance, changing tennis technique to balance foot support, trunk rotation and arm contribution, instead of getting the force and speed out of the arm mostly. Even consider proper support by footwear, appropriate for the activity. |
| The ECRB muscle has premier force generating potential, especially isometrically, independent of elbow position.<br>The position of least mechanical advantage for the ECRB is its fully stretched position, wrist flexion, and to a lesser extent, wrist ulnar deviation. | Forceful exertions combined with forceful lifting, high force activities in combination with forceful forearm pronation and supination and power grip<br>Manual labor, non-neutral hand positions, use of heavy tools, use of gloves, hand activity with precision, and/or frequent handling of loads | • Lessen forcefulness pronation and supination while holding a weight or tool, possibly by adjusting the force lever of the tool.<br>• Recommend use of power tools for activities that require pronation or supination.<br>• Assess gloves for appropriate fit and least amount padding/thickness to minimize co-contraction intensity.<br>• Be cognizant that hand activity with precision requires constant wrist stabilization. Intense concentration may distract from keeping breaks or changing position.<br>• Avoid lifting or precision manipulation with a fully flexed wrist. |
| The extensor carpi radialis longus (ECRL) has higher force-generating potential at larger angular velocities, and over a larger range of motion.<br>The ECRL divides force production over elbow and wrist extension and wrist radial deviation.<br>For the ECRL, the position of least mechanical advantage is wrist flexion, wrist ulnar deviation, and elbow extension. The ECRL loses its full force with the extended elbow. | Forceful lifting and placing loads in a far reach | • Avoid lifting or activities that start with elbow and wrist flexion and finish with elbow extension (ex: hair stylist blow drying long hair).<br>• Avoid hand manipulation with a fully flexed wrist combined with a fully extended elbow.<br>• Avoid lifting starting with an extended elbow at a distance with speed (ex: hauling in a fish). |
| Simultaneous gripping of a handle and twisting the handle requires high ECRB activity.<br>Moderate activity of the ECRB occurs with supination and pronation, even without gripping. | Forceful exertions combined with forceful lifting, high-force activities in combination with forceful forearm pronation and supination and power grip | • Lessen intensity of forceful simultaneous gripping and with pronation and supination.<br>• Recommend power tools for activities that require forearm rotation.<br>• Also think about sports activities, such as backhand stroke or pull-through with golf.<br>• Consider using kinetic chain rather than forearm to lessen excursion of pronation and supination. For instance, change tennis technique to balance foot support, trunk rotation, and arm contribution to the force application to the racket, instead of getting the force and speed mostly out of the arm. |
| Higher force production takes place during eccentric contractions for ECRB and ECRL. | Repetitive movement with eccentric wrist extensor contractions | • Avoid or modify activities that require full-length weighted stretch of ECRL and ECRB.<br>• Seek design solutions so that objects do not need to be lowered manually at a fast rate. |
| The synergy of the ECRL and ERCB is a useful mechanism for optimal function at higher angular velocities. | High rapid rate of force development, high wrist angular velocity<br>Ballistic motions | Patients and workers may intuitively use this often; for instance, when using a mouse set far at the side, but it comes with compression and shearing risks (based on personal observations). |

(*continued on next page*)

**Table 5** (*continued*)

| Muscle contraction: force, speed, type of contraction | | |
|---|---|---|
| Biomechanical risk findings: Body function | Population risk findings: Activities | Integrated considerations to alter body functions during activities to protect elbow tissue structures |
| Function of the elbow does not occur in isolation and is impacted by total body movements; vice versa, elbow (dys)function impacts the total kinetic chain.<br>Coordination between finger/wrist flexors and extensors. | Exposure studies find a combination of shoulder, elbow, and wrist functional loss and pain.<br>Forceful gripping when using gloves | • Assess and instruct in total body mechanics and posture.<br>• Assess and design workplace/work tools so that the worker can adjust to neutral body positioning that can be sustained.<br>• When instructing in shoulder strengthening exercises during recovery phase, avoid holding weights or using resistive bands while extending the elbow (eliminate shearing).<br>• Assess grip size to minimize ECRB stabilization force production.<br>• Recommendation for racket grip size (including wrap): when gripping the racket, the width of the fifth digit (of the contralateral hand) should fit between the longest finger and the thenar eminence. |
| **Biomechanical risk findings: Body function** | **Population risk findings** | **Integrated considerations to alter body functions during activities to protect elbow tissue structures** |
| The ECRL and the ECRB both provide perpendicular compression on the capitellum, with the ECRL overlying and compressing the ECRB. | Reaching and manipulating objects (with or without load) with a fully extended elbow (ex: frequent bed-making by nursing staff or hotel workers) | • Eliminate or lessen compression by lessening the load of manipulating objects with fully extended elbow.<br>• Lessen compression of the ECLR on the ECRB by keeping the elbow bent between 30° and 90° flexion (not fully extended).<br>• Environment modifications and/or tool adaptation<br>• Manipulate objects with neutral forearm rotation.<br>• Allow workers/musicians/athletes “latitude,” control to vary position during the activity. |
| The underside ECRB shears directly over the capitellum, with compressive forces added by contraction of the ECRL. | Reaching and manipulating objects with a fully extended elbow position, worsened with increasing loads<br>Repeated elbow flexion and extension | • From 30° of elbow flexion, the ECRL starts to bowstring off the ECRB and the capitellum, decreasing compression load.<br>• Lessen compression and shearing of the ECLR on the ECRB by keeping the elbow bent between 30° and 90° flexion while manipulating objects.<br>• Assess and adjust the environment to lessen far reach, eliminating last 30° of elbow extension. |
| Wrist flexion, with the fully extended elbow and fully pronated forearm, causes the most compression on the underneath side of the ECRB and the EDC, and maximum shearing against the capitellum when, in addition, the radial head moves dorsally with elbow extension.<br>Varus stress adds to stress on the bony structures. | Reaching and manipulating objects with a fully extended elbow position while moving between wrist flexion and extension | • Lessen compression and shearing of the ECLR on the ECRB by keeping the elbow bent between 30° and 90° flexion while manipulating objects, gripping, or lifting.<br>• Assess and adjust the environment to lessen far reach, eliminating last 30° of elbow extension (ex: lower chair of customer for hairdresser).<br>• Fit work environment to worker dimensions to lessen the need for far reaching.<br>• Observe that gravity does not place full varus stress when tools are being held during activities (including power tools). |
| The magnitude of the shearing force is related to the magnitude of the compressive force as well as the speed of the motion. Shearing and compression forces increase with increasing force and speed.<br>(No biomechanical studies were found to address impact of vibration on wrist extensor tendon tissues). | Ballistic movements<br>High-impact activities during sports, such as catching a ball against a racket<br>Use of hand-held vibrating tools | • Lessen compression and shearing of the ECLR on the ECRB by keeping the elbow bent between 30° and 90° flexion.<br>• Kinetic chain interventions to divide fast force production over total body. For instance: improve tennis technique to hit the ball in the “sweet” spot, where the tension can absorb most of the impact (similarly with a golf club).<br>• Consider tool adjustment to dampen vibration (such as vibration-dampening hammers, shock absorbers). |

ECRB = extensor carpi radialis brevis, ECRL = extensor carpi radialis longus

of elbow flexion. Table 5 integrates and synthesizes biomechanical and population findings resulting in theoretical and, where possible, science-based suggestions for alterations during work-related, musical performance, or sporting activities.

Use of the NIH framework of behavioral study designs provided opportunity to examine the progression of development and benefits and measurement used in ergonomic studies.[25]

Direct measurements to confirm the effectiveness and accuracy of implemented ergonomic adaptations were found in stage 0 and stage 1 studies. In stage 0, the basic science and proof of principle stage, intervention development consistently included measurements of motion and/or muscle activation measurements. Visualizations of ergonomic design implementations or visualizations of exercises applied in the work setting were shown in subsequent development stages to clarify resulting or used body motions. In studies where this was done,[161,163] opportunity arose to carefully assess if the applied intervention achieved intended work site adjustments or if exercise specifications avoided potentially harmful motions. For example, benefits and unintended limitations of a participatory ergonomic program were illustrated in a carefully conducted study developed with input from a group of 200 garment workers, that lead to design changes of dyeing tubs to submerge Indonesian-style garments.[161] Workers approved the tub design changes that were shown in clear illustrations. Implementation of the tub changes improved outcomes including reports of body discomfort and increased production rates. Clear mapping of body pain reported by workers over a dayshift showed a decrease of body discomfort, but also some persistence of low back pain. The included pictorial outcomes showed that the design changes did not result in an optimum neutral position for all body segments; elbows were extended, the lower back was curved, and foot support seemed decreased. In contrast, inclusion of potentially hazardous exercise motions using weights and resistive bands in the study protocol by Sundstrup et al.[163] for 66 slaughterhouse workers with chronic pain, showed that, despite inclusion of these exposures, the outcomes of the completed study still improved pain (also in the elbow region after the exercise program) sufficient in effect size to exceed improvements as compared to the ergonomic program.[163,164]

Progressing through the NIH behavioral stages showed descriptions of ergonomic developments and benefits including larger number of participants, either patients or workers without LE. Stage I studies, including case reports, showed detail of interventions allowing for a personal experience and impact on the work environment that one case can bring. It resulted in a conclusion that early detection of occupation as a problem may save costs on medical and rehabilitative services.[159] Longitudinal projects suggested the benefits of an interdisciplinary ergonomic approach to workers.[19,125,162] Stage II studies focused on the upper limb rather than the elbow alone in work populations, recognizing the impact of the total kinetic chain of movement, and showing the benefit when good methods are carefully described.[161,163] One study was found in Stage III suggesting that the type of practitioner and practice setting may influence treatment choices.[166] Stage IV studies started to include systematic reviews leading to the conclusion that a blanket statement regarding the benefits of ergonomic programs cannot be made when different methods are used for different types of workers.[149,168,175] No studies were found in the Stage V, dissemination and implementation research, but two reports gave guidance on design and conduct of ergonomic projects,[169] the research process between researchers and workers.[170]

Future research is needed to investigate if precious time during the watchful waiting period can be used to add structured ergonomic exploration to benefit patients. The concept of instructing patients to conduct a full inventory[169] not only of painful motions, but also of at-risk motions, is possible when patients are educated and understand the exact hazardous component within motions and activities. Bachman[176] showed an example of how an explorative dialogue between patient and therapist during ongoing tissue-based treatments could guide a plan for a vocational activity adaptation by the patient to influence recovery and potentially enable vocational activity. The human factors approach to conduct a full inventory is mentioned by only a few as a first approach.[24,159,160,177]

It is not known if patients, workers, athletes, or musical performers can self-assess frequency and duration of hazardous activities accurately to estimate a dosage of exposure experienced during a day or work cycle. Future research may address whether

**Fig. 5.** "Newly designed stands for potting plants. The stands hold the plant bins at an angle. The slope lets gravity move the plants to the front of the bin so that the plants are always close to the worker and reaching is minimized." Comments: high stools provide latitude (control) for the worker to alternate sitting and standing, and control distance away from the stands to accommodate for body size. Still stands are somewhat far removed from the worker. From: Simple Solutions: Ergonomics for farm workers. Edited by Sherry Baron, Cheryl F. Estill, Andrea Steege, Nina Lalich. https://www.cdc.gov/niosh/docs/2001-111/default.html

exertional scales such as the HAL,[119,120] the COSI, and subsequent RSI[98,142,143] can be used by patients with LE and therapists to estimate and rank order the exposure to potential harm in a certain time frame. Measurements used in sports are similar in concept, but different in nature. In contrast to the industrial measurements, in sports the load was measured as the numbers of balls thrown, not as the numbers of hand/arm activities.[178] A rating scale to define exposure developed for performing artists was not found. Further studies are needed to assess the abilities of patients to establish a full inventory and rank order hazardous motions. Rank ordering the magnitude of the perceived dosage of exposure of each motion or activity could guide a patient and therapist to prioritize activities and motions requiring adjustment.[98,142,143]

The review confirms the need for improved specification in future studies for ergonomic interventions, echoing statements noted for patients with LE[179] and patients with hand injuries.[180] Rost and Alvero[181] advocated for unifying behavioral safety and participatory ergonomics research and strategies to provide programs to manage occupational concerns. Participatory ergonomics interventions may be feasible to conduct and effectively modify risk factors for musculoskeletal disorders, including LE,[182,183] but it cannot be counted on that workers or patients have sufficient knowledge of kinetic chain biomechanics to design interventions that are safe for the total kinetic chain. Thus, collaboration between health care professionals, such as occupational and physical therapists, physicians and engineering professionals may be of great value for preventing and reducing symptoms, because unique assessment and intervention approaches of each discipline.

The role of the environmental context cannot be overstated as a risk or benefit for patients with LE. Studies demonstrating the long term impact on posture and movement due to the physical environment are needed, because strength and posture training may not be able to overcome a poor ergonomic design.[184,185] Alteration to the environmental context may positively benefit the total kinetic movement chain; for example the standing and sitting office desk has improved issues in the shoulders and upper and lower backs of workers without implementing physical training.[185]

Eliminating all potentially hazardous motions may not be feasible during all activities at all times, as demonstrated in Figure 5 taken from the National Institute of Occupational Safety and Health,[186] where a slanted stance lessens the reach of female workers potting plants, and gives the workers latitude to sit or stand when working. Even when reaching forward, the elbow does not fully extend. However, the worker still must reach over the plants that need to be potted, which may impact the reaching distance of women with larger waist circumferences.

There were unexpected findings. Personal factors, characteristics that may directly impact ergonomic design, were rarely reported in ergonomic or exposure studies; height and waist circumference descriptions, commonly already taken as a health-risk measure were not found, and body mass index was sparsely noted. Persons with a larger waist circumference will also stand or sit at a further distance from the work compared to persons with smaller waist circumference, having to reach further to complete activities, possibly exposing them to object handling with a fully extended elbow.

There were limitations to this review. We did not focus on whether ethnic and racial background contributed to the onset or recovery of LE expanding as epidemiological studies.[187] The review method evolved into an integrative review rather than that is was designed prospectively. Even though recognized methods were used, it may be that if we had applied this method prospectively, planning may have resulted in closer adherence to recent guidelines.[171,188]

Our review of tissue-specific treatments focused on the mechanism of interventions and was limited to publications between 2000 and 2021, and can therefore not provide clinical practice guidelines for tissue based treatments. We did not conduct an in-depth search for specific information about the role of Functional Capacity Evaluation in preventing LE in workers. A thorough review of medical and surgical techniques to enhance healing of lateral elbow pain was not conducted for this paper. The debate about the use of local or systematic nonsteroidal anti-inflammatory drugs (NSAIDS) and corticosteroid injections is addressed in other reviews.[189,190] In-depth review and interpretation of the benefits of injections with autologous blood or platelet-rich plasma [191-196] or botulinum toxin injections[197-199] are offered in other sources. An in-depth review and interpretation of current developments of surgical interventions are also beyond the scope of this report and is addressed elsewhere. Lastly, we did not focus on the non-surgical treatment of enthesopathy of the ECRB.[44,111,200-202]

Reviewing the efficacy of all possible ergonomic interventions that are available and commercially for sale could not be done. Good governmental resources addressing alternate designs are available for the public, for workers, employers, and healthcare professionals and researchers alike. The U.S. Bureau of Labor Statistics offers standardized descriptions and informative illustrations of work demands for a series of occupations that require basic body movements.[203] The website of the National Institute for Occupational Safety and Health provides examples of ergonomic interventions, promoting safe positioning strategies through contextual work-site adaptations per type of industry or occupation.[204] The fields of professional sports and performance should also be included more thoroughly in future reviews. Future studies may explore the validity of wearable high technology to quantify exposure for LE, such as were reviewed for the field of sports by Benson et al.[178]

Our recommendations, presented in Table 5, are theoretical considerations and suggestions derived from the anatomical, biomechanical, and population findings and outcomes of ergonomic studies, and their validity needs to be confirmed in future studies.

## Conclusions

All components of the ICF, from pathology, tissue structures, and tendon function through activities and participation in life roles, and contextual and personal characteristics, were intimately connected in the care of patients with LE. A full ergonomic inventory is suggested as an important first approach due to the potential to benefit patients in all stages of severity and recovery of LE. Future studies may address if or how repetitive motion injuries of LE are cumulative in nature. Collaboration between health care professionals and engineering professionals may be of great value for workers, athletes, performing artists and patients with existing LE in primary or secondary prevention of LE, because each discipline may contribute with its unique approach.

Therapists may use their knowledge of biomechanical and population-based risk factors to guide patients to formulate a personal inventory of tendon tissues tissue-oriented risk factors to minimize these risk factors for LE: muscle force and subsequent tendon stress, excessive tendon strain, tendon compression, and tendon shearing. It is hoped that, tendon- , motion- and activity-specific information and education may transform patients into change agents who with positive attitudes and positive phrasing skills,[205] supported by latitude, choice, and control within the occupational environment, encouragement, respect and social support, can cope with and recover from their personal lateral epicondylosis.

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## Appendix

**Table 1**
Pathology studies of lateral epicondylosis (LE)

| First author, year | Study purpose | Type study subjects/specimens | Measurements | Results |
|---|---|---|---|---|
| Pathology | | | | |
| Goldie 1964 | Pathogenetical study for LE | Observational cadaver material and intraoperatively obtained tissues<br>Clinical examination of 154 patients with LE resulting 113 surgery cases (114 elbows)<br>Control cases interviewed premortem to have had no LE, 31 cadavers (62 elbows) | Macroscopic and microscopic observations, vascular, dry weight for edema, granulation tissue, nerve investigation<br>Physical examination: pain, grip strength, histology | Controls: tendon with tendinous plate (aponeurosis)<br>Extensor carpi radialis brevis (ECRB) degeneration occurs with age > 50 (not the peak years for LE), therefore age > 50 not a factor for LE<br>LE: edema in aponeurotic tissues, underneath aponeurosis granulation tissue, with fibrosis, and free nerve endings (pain), hypervascularization of the aponeurosis |
| Ljung Forsgren, Friden 1990 | To describe substance P and calcitonin gene-related peptide (CGRP) in patients with LE and healthy subjects | Cross-sectional cohort comparison of 6 patients intra-operatively, and biopsies of 6 healthy volunteers<br>Specimens from patients included area close to the bone, but area close to the bone was not included in healthy subjects | Histology procedures and measurements<br>Observations, histology of substance P and CGRP (these have dual function: transmit nociceptive information to the spinal cord, and are involved in vasodilation and plasma extra vacation, neurogenic inflammation) | The pattern of substance P and CGRP in patients with LE were the same as in healthy controls, confirming that LE is not an inflammatory disease. The proximal attachment of the ECRB is supplied with substance P/CGRP innervation, which may have an important contribution to the efferent effects of pain to the spinal cord. |
| Ljung, Lieber, Friden 1999 | Describe morphology of the ECRB muscle in patients with LE and controls | Cross-sectional study comparing tissues of patients with LE to normal without LE; intraoperatively collected of 20 patients with chronic LE during surgery for distal lengthening.<br>Controls: 5 healthy volunteers, 4 autopsy samples. | Light microscopy; structural abnormalities: (0 = no abnormalities, 1 = occasional i.e., in less than 3 fascicles per sample, 2 = in every fascicle)<br>Fiber type: muscle fiber type grouping was defined as fibers of one single type that appeared immediately adjacent to each other, forming a distinct group of one single fiber type. | Morphological abnormalities were significantly more frequent in patients than controls and included "moth-eaten" fibers, fiber necrosis and signs of muscle fiber regeneration as well as higher percentages of the fast-twitch oxidative (type IIA) fiber type. Changes were equally distributed proximally at the elbow and distally at the wrist. |
| Connell 2000 | Describe sonographic appearance of extensor digitorum communis (EDC) origin of patients and control volunteers | Observational<br>Patients with LE: 71 patients, 72 elbows<br>Controls: 10 asymptomatic volunteers, 3 cadavers | (1) Ultrasound imaging scale of severity: tendon enlargement compared to unaffected, tendinopathy mild (< 30% of fibers affected), moderate (30-70%), severe (> 70%); (2) calcification, bony changes, echogeneity | Controls: Longitudinal fibers of the common extensor attachment are bound with the ECRB; ECRB deepest, closest to the bone, EDC most superficial. The lateral collateral ligament is a separate band.<br>LE: Focal hypoechoic area in the deep part of the tendon, collagen degeneration with fibroblastic proliferation. Cleavage planes traversing the tendon showed partial and complete tears. The lateral collateral ligament was involved in some patients. |
| Fairbank 2002 | Test that a positive Maudsley' test (long finger extension) is indicative of EDC of the long finger pathology rather than ECRB. | Cadaver and clinical study<br>Patients: 10 patients with LE, ages 25-51Y old<br>Controls: 12 preserved and 1 fresh cadaver specimen | Cadaver: dissections elbow through forearm; EDC, EDF- middle finger (MF), ECRB, extensor carpi ulnaris (ECU)<br>Clinical: isometric extension of wrist and fingers, visual analog scale (VAS) pain scores<br>Wilcoxon signed rank tests to test differences in VAS as confirmation. No sensitivity or specificity. | Cadaver: EDC middle and index finger separately join into the keel of the ECRB<br>EDC-MF originated from the LE, had some fibers to the supinator muscle, EDC-index did not attach to the LE, but distally onto the ulnar side of the ECRB aponeurosis. EDC ring and small do not attach to the LE, but to aponeurosis of ECU.<br>Clinical: Highest pain score with resisted wrist extension, followed by EDC-MF resisted extension |
| Alfredson 2000 | Study neuro-transmitter glutamate and prostaglandin $E_2$ in patients with LE and controls using micro-dialysis | Group comparison between 4 patients with LE and 4 healthy control subjects, experiment stopped due to lingering pain in controls | Measurement of neuro-transmitter glutamate (pain) and prostaglandin $E_2$ ($PGE_2$ ) active in inflammatory reactions) with micro-dialysis over 2 H | ECRB tendons of patients had higher level of glutamate than controls. No difference in $PGE_2$ between groups. Since inflammation was not confirmed, agents other than non-steroidal anti-inflammatory drugs and local corticosteroid injections (with fewer side effects) may be used for patients. |

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**Table 1** (*continued*)

| First author, year | Study purpose | Type study subjects/specimens | Measurements | Results |
|---|---|---|---|---|
| Chourasia 2013 | Investigate relationships between tendon pathology, biomechanical measures, and self-reported pain and function in patients with LE | Single cohort descriptive and correlational study<br>26 patients with chronic LE (unilateral 11; bilateral 15) | Magnetic resonance imaging (MRI) scale: 0-3 (0 no abnormalities, 3 severe tendinopathy), thinned tendon affecting more than 50% of the total tendon cross-section<br>US scale: neovascularity (0-3), hypoechogenicity (0-3) | Imaging scores of tendon pathology were not significantly associated with grip strength, force generation, or patient self-reported pain. |
| Van Leeuwen 2016 | Test MRI signal changes in the ECRB with advancing age in patients without LE; testing signal changes in “true” negatives | Retrospective study 3374 medical records of MRI rating of patients without LE, seen for other elbow problems | MRI (proximal ECRB, common EDC, enthesis close to the ECRB)<br>Age, gender, race | 369/3374 (11%) had degenerative signal changes in the ECRB proximal attachment. Prevalence increased from 5.7% in subjects 18-30 Y up to 16% in subjects > 71 Y.<br>Older age (odds ratio, 1.04; P < .001) was associated with the finding of ECRB enthesopathy on elbow MRI scans. Increased MRI signal in the ECRB origin is common in asymptomatic elbows. |
| Bachta 2017 | To investigate reliability and diagnostic validity of US in detecting and grading common extensor tendon tear (CET) in patients with chronic LE | Cross-sectional study; standardized measurement, all measured by the same experienced rater<br>Subjects: 58 patients with chronic LE<br>MRI used as comparison gold standard | MRI and US same scaling: (0) no CET, (1) suspected CET tear (possible but not evident CET tear), (2) low-grade tear (involving < 50% of the CET thickness), (3) high-grade tear (involving > 50% of the CET thickness). Additionally, a dichotomous scale (i.e. confirmed/ unconfirmed tear) | MRI: 44/58 with tear (75.9%)<br>US: 35/58 with tear (60.4%)<br>US and MRI: moderate agreement in detecting and grading CET tear ($\kappa = 0.49$)<br>US: sensitivity, specificity, and accuracy: 64.52%, 85.19%, and 72.73%, respectively<br>Positive predictive value and negative predictive value: 83.33% and 67.65%, respectively |
| Palaniswamy 2018 | Investigate relationships between tendon structural changes (US) and sensory changes and clinical measures in LE | Cross-sectional study<br>Affected and unaffected elbows of 66 patients with clinical LE; 10% of patients had bilateral LE<br>9 patients (13.6%) had a previous corticosteroid<br>injection > 6 mo ago<br>Duration of symptoms: mean 50.8 wk, standard deviation 2.9<br>Blinded experienced raters | Total US scale: (hypoechogenicity, neovascularity, heterogeneity, bony abnormalities, tendon thickness) on a scale from 1-3<br>Sensory testing: pressure pain, threshold, heat, cold pain thresholds, vibration detection threshold<br>Patient-reported scales: Patient-Rated Tennis Elbow Evaluation, quality of life (EuroQoL EQ-5D), pain-free grip strength with elbow extended and forearm pronated | LE elbows: grade 3 hypo-echogenicity (72.7%), absence of neovascularity (81.8%), insertional bony abnormalities (74.2%) were the most prevalent ultrasound findings<br>Controls unaffected elbow: grade 2 and 3 hypo-echogenicity (44.6% each), absence of neovascularity (87.5%) were the most common US findings<br>LE elbows: more sensitive to cold as compared to not affected<br>Conclusion: structural and sensory measures were weakly correlated. Neovascularity and transverse tendon thickness may be related to sensory system changes in LE. |
| Cha 2019 | Reliability of MRI interpretation to diagnose LE, validity of MRI to diagnose of CET injury vs CFT and other elbow abnormalities; correlations between elbow abnormalities and pain | Cross sectional, repeated measurements; 3 blinded raters; intra- and interrater reliability<br>51 patients with LE (status post < 3 months after cortisone injection excluded) | MRI: (1) degrees of CET and ligament injuries (classified as<br>mild, moderate, or severe); (2) presence of muscle, cartilage, and bone injuries; (3) joint effusion; (4) bone abnormalities on radiographs<br>Patient-reported: VAS (0-10, 11 point) | Intraobserver ICC: > 0.9<br>Interobserver ICC: 0.89<br>Observations: CET: 50/51= 98%, radial/lateral ulnar ligament: 41/51= 80%, enthesophyte or calcification 13/51 (25.5%). CFT: 10/51(19.6%), medial collateral ligament: 10/51-19.6%, joint effusion 7/51 (14%), bone marrow edema in 6/51 (11%), cartilage defect in 4/51 (7%), extensor & flexor muscle injury in 3/51 (6%), anconeus muscle injury in 1 (2%). CET correlates with radial and ulnar collateral injury. |

CET = common extensor tendon, CFT = common flexor tendon, CGRP = calcitonin gene-related peptide, ECRB = extensor carpi radialis brevis, ECU = extensor carpi ulnaris, EDC = extensor digitorum communis, LE = lateral epicondylosis, MF = middle finger, MRI = magnetic resonance imaging, US = ultrasound, VAS = visual analog scale

**Table 2**
Studies to explain muscle and tendon biomechanics relevant to lateral epicondylosis (LE)

| Author, year | Study purpose | Type study subjects/specimens | Measurements | Results |
| --- | --- | --- | --- | --- |
| Muscle biomechanics | | | | |
| Brand 1981 | Investigate tissue characteristics and the muscle force balance between elbow, forearm and hand muscles for the purpose of finding a muscle tendon transfers in the paralyzed hand, causing the least functional loss | Explorative comparative design comparing resting fiber length; mass fraction % and tension fraction % 15 cadaver limbs; dissection fibers muscles extensor carpi radialis longus (ECRL) and extensor carpi radialis brevis (ECRB) | Dissection fibers muscles physiological cross-section; parameters as % to allow multiple sample comparisons Muscle: (1) work = force X distance work mass fraction: weight of a muscle as a % of total forearm muscle weight, (2) cross-sectional area of all fibers is proportional to maximum tension. Tension fraction: cross-section area for one muscle as percentage of total area of all forearm muscles, (3) mean fiber length is proportional to potential excursion. | ECRL and ECRL different muscle characteristics: ECRL fiber length 50% more than ECRB, tension fraction less than ECRB Work mass fraction: ECRB 5.1, ECRL 6.5 Tension fraction: ECRB 4.2, ECRL 3.5 Mean fiber length cm (excursion): ECRB 6.1, ECRL 9.3 (range 6.3 distal-12.3 proximal end) "ECRB is the work horse of the wrist," with force production independent of elbow position. |
| Lieber, Ljung, Friden 1997 | To investigate differences in sarcomere length changes in the ECRB and ECRL during passive wrist rotation. | Repeated measures of sarcomere length changes with passive wrist flexion extension (with the elbow fixed in 20 degrees of flexion) Subjects: 7 subjects with radial nerve releases at the level of the supinator fascia. Intra-operatively measured. | Laser prism measurements of sarcomere length Slope of sarcomere length change in ECRB and ECRL per joint angle change | Sarcomere length change per degree of rotation was about twice as great for the ECRB compared to the ECRL muscle. ECRB and ECRL are efficient synergists; the ECRB is stronger isometrically, the ECRL becomes the stronger muscle as angular velocity increases. The synergy of the ECRB and ECRL takes 30% less mass in comparison to if one muscle would generate the force. |
| Ljung 1999 | To measure sarcomere length change in the ECRB muscle during ulnar deviation with the wrist in both the neutral and pronated position. | Repeated measures of sarcomere length changes in 4 conditions: (1) wrist in neutral (in radial-ulnar and forearm in neutral rotation), (2) forearm neutral rotation + wrist in ulnar deviation, (3) wrist in neutral + forearm in pronation, and (4) wrist in ulnar deviation and forearm in pronation 7 patients with LE prior to surgery, measured intra-operatively during distal tendon lengthening | Sarcomere length in vivo in resting position, with elbow in 20 degrees of flexion. Authors measured what is anatomically possible and caution that may or may not actually happen in vivo. | Two-way analysis of variance result: significant effect of ulnar deviation ($P < 0.05$), no significant effect of pronation ($P = 0.7$) and no significant interaction ($P = 0.9$) ECRB sarcomere length increased with ulnar deviation from either the neutral or pronated position. The axes of forearm rotation and wrist radial-ulnar deviation act independently, with regard to the ECRB. Forearm rotation as a risk factor for tennis elbow is not confirmed. |
| **Tendon biomechanics** | | | | |
| Briggs-Elliott 1985 | To conduct a detailed reexamination of structures relevant to LE | Observational cadaver study, 139 limbs from embalmed specimens | Dissected to reveal the attachments of extensor muscles in the vicinity of the lateral epicondyle. Illustrations and descriptions | ECRB consists of a keel-shaped tendon with attachments to ECRL, extensor digitorum communis (EDC), supinator, radial collateral ligament, orbicular ligament, capsule of the elbow joint, and deep fascia. 29/139 (20%) limbs with a more proximal attachment to the lateral epicondyle 9/139 (5%) limbs with a bursa between the capsule over the head of the radius and the overlying soft tissues Shearing: There were connections between ERCB, EDC and ECRL; thus, contractions of those will exert unequal tension and shearing. ECRB shearing over radial head with pronation. Elbow position does not impact ECRB lengthening by itself, but completes full ECRB lengthening when combined with pronation, wrist flexion and ulnar deviation. |

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**Table 2** (*continued*)

| Author, year | Study purpose | Type study subjects/specimens | Measurements | Results |
|---|---|---|---|---|
| Greenbaum 1999 | Describe the gross and microscopic anatomy of the ECRB origin and its relationship to the surrounding muscles and elbow capsule. Determine the site of the pain of LE | 40 fresh-frozen cadavers | Dissected from distal to proximal to reveal the attachments of extensor muscles in the vicinity of the lateral epicondyle | 30 of 40 (75%) limbs showed that the smaller ECRB tendon mixes with aponeurosis of EDC.<br>Lack of separation between ECRB and EDC at osseous-tendinous junction, but separation between ECRB, ECRL, and extensor carpi ulnaris (ECU)<br>No connection with collateral ligaments<br>10 of 40 (25%) of the ECRB under the muscle belly of the ECRL, EDC<br>Given the intimate relationship between ECRB and EDC, the ERCB may not be the only cause for lateral elbow pain. |
| Bunata 2007 | Shear and compression: study the anatomy of the lateral aspect of the elbow under static and dynamic conditions in order to identify bone-to-tendon and tendon-to tendon contact or rubbing that might cause abrasion of the tissues | Repeated measures design, 85 embalmed cadaveric elbows<br>Elbows: 90°, 45°, 30°, 0° of flexion<br>Positional relationships of the capitellum, the ECRL, ECRB under 3 conditions: ECRB + ECRL, ECRB, ECRL alone<br>Injection study to visualize rubbing, compression with pronation, supination | Dissections done under loupe magnification; standardized photography, standardized grid of measurement | The tendinous attachment of the ECRB was positioned deep and superior within the stout tendon of the EDC and ECU.<br>Average site of origin of the ECRB on the humerus is slightly medial and superior to the outer edge of the capitellum.<br>With elbow extension, the undersurface of the ECRB rubs against the lateral edge of the capitellum, while the ECRL compresses the ECRB against the underlying bone. Bowing and stretching of the tendons over the epicondyle and the capitellum occurs with the elbow in full extension.<br>Conclusion: the ECRB tendon has a unique anatomic location that makes its undersurface vulnerable to contact and abrasion against the lateral edge of the capitellum during elbow motion. |
| Tanaka 2011 | Shearing and compression; to evaluate the effect of the position of the elbow and forearm on the contact pressure of the tendinous origin of the common wrist and finger extensors | 8 fresh frozen cadavers without signs of arthritis, brachialis removed, but ECRL, ECRB, EDC, ECU left in place<br>4 elbow flexion angles: 0°, 30°, 60°, 90°, 2 forearm rotation angles: 81.5° pronated, neutral forearm pronation, and 3 varus stress loads (none, gravity of the arm, and gravity plus 19.6 N) | Pressure sensor placed between the undersurface of the common extensor tenson and the lateral side of the capitellum (1 cm distal to the lateral epicondyle and 3 mm posterior from the lateral edge of the capitellum) | Elbow position: contact pressure greatest between 0° and 30° of elbow flexion, pronation and varus stress<br>Contact pressure lowest with 90° elbow flexion, forearm neutral position, and with no varus stress load<br>Support recommendation to refrain from lifting with the forearm pronated and elbow extended, cautions to prevent varus stress loads |
| Nimura 2014 | (1) Analyze specific anatomical features of the ECRB, (2) identify relationships between the ECRB origin and the deeper structures, such as the joint capsule and the supinator. | Explorative cadaver study, 23 arms of 17 cadavers; excluded 3 arms with capsular tears at the attachment under the ECRB | Macroscopic dissection<br>Muscles assessed: brachialis (BR), ECRB, ECRL, EDC-extensor digiti minimi (EDM)<br>Histological examination of 4 of 23 arms | BR and ECRL: attachment lateral supracondylar ridge of the humerus with large muscular portion. The EDC/EDM attach to lateral epicondyle just distal to ECRL.<br>The ECRB has a thick tendinous portion without any muscular portion, was thickest at its origin and gradually transitioned into muscle.<br>At the anterior part of the ECRB origin, a thin attachment of the joint capsule lays deep to the ECRB and was distinct.<br>On both sides of the ECRB origin, the joint capsule, annular ligament, and supinator formed a continuous structure. |

BR = brachialis, ECRB = extensor carpi radialis brevis, ECRL = extensor carpi radialis longus, ECU = extensor carpi ulnaris, EDC = extensor digitorum communis, EDM = extensor digiti minimi

**Table 3**
Investigations of risk activities and exposure characteristics in various populations

| AUTHOR/YEAR | PURPOSE | DESIGN SUBJECTS | EXPOSURES | EXPOSURE MEASUREMENTS | RESULTS |
|---|---|---|---|---|---|
| Ranney et al. 1995 | Detail upper-limb musculoskeletal disorders (MSD) in female workers with highly repetitive jobs | Cohort study (cross-sectional) 146 female workers | • Garment sewing<br>• Auto trim<br>• Electronics assembly<br>• Metal parts assembly<br>• Cashiering<br>• Packaging | Worker: structured interviews, physical examination<br>Environment: plant walk-through, workstation observation<br>Hazards in the workplace: accident statistics, interviews of supervisors, videos of workers | 54% of workers with work-related upper limb MSDs (33% bilaterally); predominance of forearm extensor and epicondylar disorders; assessments need bilateral exposure measures and consideration of static postures |
| Latko et al. 1999 | Determine relationship between exposure to physical stressors and prevalence of work-related MSDs in industrial workers | Cohort study (cross-sectional) 352 workers from 3 manufacturing companies | • Repetition<br>• Other physical stressors | Worker: demographic questionnaire, physical examination, limited electrodiagnostic testing<br>Environment: walk-throughs, observations<br>Hazards in the work: observational rating for repetitive exposure, 0 (no stress) to 10 (maximum stress) | Repetitive work is related to upper limb discomfort, tendinitis, and carpal tunnel syndrome in industrial workers. |
| Moore et al. 2001 | Evaluate and compare the generic risk factor method and the Strain Index (SI) | Cohort study (cross sectional) 56 types of jobs | Manufacturing plants:<br>• Chairs<br>• Connectors and hoses<br>• Turkey processing | Worker: repetitiveness, forcefulness, pinch activities, use of gloves, intensity rating, Borg Rating, non-neutral wrist posture, vibrating tool, contact with hard or sharp surfaces, cold exposure<br>Environment: hazard classification of the job, Morbidity classification of the job, Occupational Safety and Health Administration data<br>Hazards in the work: videotapes, 2 observers, Strain Index | Provides evidence of external and predictive validity of the SI; most favorable predictive validity involves use of gloves (generic risk factor) and SI score |
| Haahr & Andersen 2003 | Assess physical and psychosocial risk factors for lateral epicondylitis (LE) | Case-control study (case referent) 483 subjects | Strenuous vs. non-strenuous upper extremity tasks<br>Physical workplace factors | Worker: demographic questionnaire, pain assessment, structured interview, self-reports (leisure, sports, and physical activity)<br>Environment: worksite visits<br>Hazards in work: SI, job descriptions, Karasek & Theorell job content questionnaire, job satisfaction survey | Supports association between manual labor, non-neutral postures, use of hand-held tools, high physical strain, and LE; among women, repetitive movements and low social support were related to LE; among men, work with precision demanding movements related to LE |
| Walker-Bone & Cooper 2005 | Review occupational associations with MSDs of the neck and upper limb | Cohort study<br>Epidemiological surveys of neck or upper limb complaints | Neck or upper limb complaints | Worker: classification of neck/upper limb soft tissue disorders<br>Hazards in work: assessment of exposures (combinations of force, repetition, and/or vibration) | Neck/upper limb pain common among working adults; MSDs associated with abnormal posture, repetition, and low psychological wellbeing |

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**Table 3** (*continued*)

| AUTHOR/YEAR | PURPOSE | DESIGN SUBJECTS | EXPOSURES | EXPOSURE MEASUREMENTS | RESULTS |
|---|---|---|---|---|---|
| Shiri et al. 2007 | Investigate role of hand dominance in upper extremity MSDs | Cohort study (cross-sectional, prevalence) 6254 subjects | Work-related physical load factors in current and former jobs | Worker: hand dominance, interview, health examination, upper extremity symptom screening, standardized physical exam | LE more prevalent in dominant elbows in both genders |
| Fan et al. 2009 | Identify risk factors for LE in active workers | Cohort study (cross-sectional, prevalence, and predictive) 733 workers in 12 worksites | Manufacturing:<br>• Electronics<br>• Auto parts<br>• Windows<br>• Cabinets<br>• Medical equipment<br>• Fitness equipment<br>Healthcare (excluding direct patient care):<br>• Hospitals<br>• Health research | Worker: structured interviews, physical examinations<br>Environment: workplace walk through<br>Hazards in work: individual assessments of biomechanical and psychosocial factors | LE related to frequency of forceful exertions or forearm supination and forceful lifting; increased odds of LE related to being age 36-50, female, or a smoker; high social support appeared protective against LE |
| van Rijn et al. 2009 | Assess relationship between work-related physical factors, psychosocial factors, and LE | Systematic review<br>13 studies:<br>• 9 cross-sectional<br>• 2 case–control<br>• 2 cohort | Physical exposures (force, repetitiveness, vibration, posture) | Workers: handling tools, high hand grip forces, repetitive movements, arm lifting or hand bending, vibrating tools, job control, social support, depression, job demands | Postural load, low job control, and low social support associated with LE; frequent handling of loads, highly repetitive movements, and forceful work associated with both LE and medial epicondylitis |
| Walker-Bone et al. 2012 | Explore relationship between occupational exposures and epicondylitis | Cohort study (cross-sectional) 9696 men and women | Manual work and repetitive bending and straightening of elbow | Worker: structured interview, clinical examination (Southampton examination protocol)<br>Hazards in work: screening questionnaire (mechanical and psychosocial factors) | LE associated with manual work and repetitive bending and straightening the elbow $>$ 1 H day |
| Descatha et al. 2013 | Test for suspected physical exposures that may lead to LE in a large population of workers | Cohort study (longitudinal) 1107 newly employed workers | • Manufacturing<br>• Construction<br>• Biotechnology<br>• Healthcare | Worker: demographic questionnaire, health history, UE symptom checks, physical exam, social support scale, self-reported physical exposures (bending, rotating, or gripping)<br>Hazards in work: categorized as none or $<$ 1 H/D, 1-2 H/D, 2-4 H/D, or $\geq$ 4 H/D | Repetitive and prolonged wrist bending/twisting, and forearm movements associated with LE |
| Herquelot et al. 2013a Am J Ind Med 56:400–409 (2013) | Assess relationships between work-related physical and psychosocial factors and elbow disorders | Cohort study (cross-sectional) 3710 workers (42% female) | Physical load and psychosocial factors | Worker: physical examinations, questionnaire assessing personal factors and work exposures | Emphasizes association between physical exertion, elbow movements, and LE; hard physical exertion combined with elbow and wrist motions for $>$ 2 H/D increase the risk for LE |

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**Table 3** (*continued*)

| AUTHOR/YEAR | PURPOSE | DESIGN SUBJECTS | EXPOSURES | EXPOSURE MEASUREMENTS | RESULTS |
|---|---|---|---|---|---|
| Herquelot et al. 2013b Scand J Work Environ Health 39(6):578-588 | Estimate association between occupational risk factors and incidence of LE | Cohort study (cross-sectional and incidence) 3710 workers; 1046 completed follow-up | Repetition, physical exertion, arm movements | Worker: health assessment Hazards in work: self-reported | Repetitive tasks and high physical exertion with elbow movements contributed to incidence of LE |
| Nordander et al. 2013 | Explore relationships between occupational risk factors and MSDs of the elbow and hand | Cohort study (cross sectional and prevalence) 8 groups of male workers (n = 761); 19 groups of female workers (n = 1891) | Physical workload factors | Worker: Swedish version of Job Content Questionnaire Environment: observation Hazards in work: workday recordings, axial flexible electro-goniometers, bipolar surface electromyography (static load, peak load, and muscular rest) | Established quantitative exposure-response relationship between physical workload and elbow/hand disorders; wrist angular velocity most consistent risk factor; wrist flexion associated with LE |
| Fan et al. 2014 Am J Ind Med 57:1319–1330 | Determine if Strain Index predicts incidence cases of work-related epicondylitis | Cohort study (prospective) 607 workers in 12 facilities | • Manufacturing<br>• Healthcare | Worker: interview on health, physical exam, Nordic Musculoskeletal questionnaire, pain body mapping, and impact on work Environment: interview, observation<br><br>Hazards in work: work history interview, Strain index | Strain Index can effectively identify jobs with increased risk of developing LE, SI > 5, older age, and self-perceived poor health associated with LE |
| Fan et al. 2014 Hum Factors 56(1):151–165 | To investigate relationships between workplace physical exposures, assessed at an individual level with LE | Cohort study (prospective) 733 at baseline, 611 after exclusions and drop out | • Manufacturing<br>• Service sector jobs | Worker: demographic interviews, history of health, sports, hobbies, and jobs; upper extremity (UE) symptom screening and impact on work; physical exposures (force, repetition, and/or combination); physical exam of neck/UEs | Found exposure-response relationships between workplace physical exposures and the presence of LE; older age and jobs requiring high force, forearm pronation, and power grip more likely to predict LE |
| Garg et al. 2014 | Quantify relationships between job physical exposures (JPE) and incidence of LE | Cohort study (prospective) 536 workers | Job physical exposure | Worker: work history, hobbies, Borg intensity scale Environment: number of tasks, length of shift, duration of each task, peak force Hazards in work: videos, JPE, hand activity level (HAL), Strain Index, and Threshold Limit Value (TLV) score | JPE, age, family problems, and swimming associated with increased risk of LE; the Strain Index, TLV, & HAL are useful metrics for estimating JPE |
| Bao et al. 2016 | Identify relationships between work variables and health outcomes | Cohort study (prospective) 1834 subjects, 35 facilities, 25 industries | Work organizational variables | Worker: questionnaires, interviews, health outcome measures Environment: ergonomists' worksite visits, observations Hazards in work: job rotation, overtime, second job, pacing | Job rotation, overtime work, having a second job, and work pacing partially associated with LE |

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**Table 3** (*continued*)

| AUTHOR/YEAR | PURPOSE | DESIGN SUBJECTS | EXPOSURES | EXPOSURE MEASUREMENTS | RESULTS |
|---|---|---|---|---|---|
| Descatha et al. 2016 | Analysis of associations between physical exposures at work and LE | Meta-analysis 5 prospective studies 6922 subjects (3449 followed) | Biomechanical exposures at work | Worker: self-report, Borg Rating Scale, clinical exam Environment: observation, identification of biomechanical risks<br>Hazards in work: elbow bending, forearm rotation, power grip, and high exertion; Strain Index | Supports association between biomechanical exposures and incidence of LE; strenuous manual tasks involving elbow, forearm, and hand motions in a high force manner for long duration increased risk of LE |
| Lee et al. 2016 | Investigate effects of wrist deviation combined with extension and movement velocity on dynamic performance of wrist muscles | Risk analysis study 30 heathy subjects | Muscle activity, movement velocity, wrist positions | Subjects: custom bi-planar isokinetic dynamometry to measure muscle strengths for the wrist extensors and flexors during concentric and eccentric contractions at three movement velocities, combined with three wrist postures | Wrist deviation combined with extension and movement velocity of the wrist joint might alter the wrist strength and muscle activity during dynamic performance and may result in injury of the elbow |
| Thiese et al. 2016 | Assess relationships between psychosocial factors and elbow epicondylitis | Cohort study (cross-sectional) 1824 participants (59.65% female) | 35 facilities, 25 industries<br>• Manufacturing<br>• Food processing<br>• Healthcare<br>• Office employment | Worker: demographic questionnaire, psychosocial questionnaire (adapted from National Institute for Occupational Safety and Health Generic Job Stress Questionnaire, the Job Content Questionnaire, and questions developed by the research team) | Demonstrated significant associations between personal, occupational, and psychosocial factors and LE; psychosocial risk factor with largest impact on LE was physical exhaustion after work |
| Aben et al. 2018 | Compared psychological profiles of persons with LE and healthy controls | Case-control study (prognostic) 69 patients (35 men, 34 women) and 100 controls (44 men, 56 women) | Psychological work exposures | Worker: interviews about work satisfaction and working conditions, self-report questionnaires: Ten-Item Personality Inventory, Frost Multidimensional Perfectionism Scale, Hospital Anxiety and Depression Scale | Persons with LE scored lower on agreeableness, extraversion, and enthusiasm; have higher anxiety and depression, and engage in repetitive work; females with LE indicated a low level of workplace autonomy and reported less social contact; males with LE were more perfectionistic and indicated higher-force workloads |
| Seidel et al. 2019 | Provide quantitative measures of physical risk factors associated with elbow disorders | Systematic review 10 articles:<br>• 5 cross-sectional<br>• 3 cohort<br>• 2 case referent (case control) | Overview of physical risk factors significantly associated with development of elbow disorders | Hazards in work: force, repetition, posture/movement, hand-arm vibration, combined factors | Extensive summary table of risk factors: patting, using the hand as a tool; overhead working, wrist extension, maximum efforts of the hand, wrist angular velocity or forearm supination; combination high physical exertion and elbow flexion/ extension and extreme wrist bending. Force combined with awkward posture or repetition may have a major impact on the development of elbow disorders. Women more at risk for forceful hand efforts as compared to men |

HAL = hand activity level, JPE = job physical exposures, LE = lateral epicondylosis, MSD = musculoskeletal disorders, SI = Strain Index, TLV = Threshold Limit Value, UE = upper extremity

**Table 4**
Ergonomic interventions listed using the framework for behavioral intervention development by the National Institutes of Health.

| Author, year | Purpose | Design/ subjects | Intervention | Measurement | Results/ outcome |
|---|---|---|---|---|---|
| Stage 0: Basic science and "proof of principle" studies | | | | | |
| Yasukouchi 1993 | Examine differences in strain of shoulder, elbow, wrist muscles (direction in the horizontal plane and increasing distance) in a reaching task to benefit teller workplace design | Repeated measurement design of activities, based on teller functional video recordings: picking up a card, picking up a stick (cylindrical seal), placing a card<br>N = 5 healthy subjects | Repeated positioning in an arc motion seated at a desk from 0° (parallel to the body) to 90° (perpendicular to body), and placing objects forward (30, 50, 70 cm) | Anthropomorphic: height, sitting height, and upper limb length<br>Surface electromyography (EMG): descending and ascending trapezius, middle and clavicular deltoid, pectoralis major, extensor carpi radialis brevis (ECRB)<br>EMG right side relative, left side at 0 and 70 cm reach | Task completion time and ECRB activity increased with increasing forward distance and sideways distance.<br>The optimum angle would be perpendicular forward to 30° angled; least effective angle (highest EMG in the ECRB) being repetitive reaching to the side, at greatest distance. |
| Fleming et al. 1997 | Study (1) the effects of wearing a work glove, (2) type of muscle contraction on handgrip fatigue, (3) examine relationships between muscle performance and subjective perceptional fatigue | Repeated measures design; with 2 factors: glove-no glove and eccentric vs isometric contractions<br>N = 21 healthy subjects (21-55 Y old; 4 males, 16 females)<br>All subjects were tested under all conditions | Subject applied force at 60% of their measured maximum in a standardized position, with the wrist in neutral, elbow bent 90°<br>Conditions were either making it for isometric or preventing that the hand would be pried open (eccentric). | (1) Mean power frequency of the electromyogram of the flexor digitorum superficialis, (2) rate of perceived effort, (3) time to limit of endurance, and (4) fatigue objective-subjective relationship | Time to limit of endurance was shorter with gloves on (earlier fatigue)<br>Results for the fatigue objective-subjective relationship is opposite to the endurance level. Unperceived fatigue may lead to difficulty in controlling or holding tools during work tasks that require eccentric action. |
| Stegink Jansen 1997 | Study the effectiveness of wrist orthoses to decrease wrist extensor muscle activity, as measured by surface EMG during simulated functional activities. | Repeated measures design: 4 conditions of wrist orthoses (dorsal, volar, semicircular, and no orthosis)<br>Subjects: 13 healthy subjects between 22-42 Y old | 3 lifting tasks (paper folder, paper grocery bag, brief case), maximum grip with elbow flexed and extended | Quantity surface EMG of wrist extensors, as measured by the root mean square (RMS) (the proximal electrode approximately 3 cm distally to the head of the radius) | (1) RMS was significantly lower during lifting tasks for the semicircular design ($P < 0.005$, power 0.92; effect size 1.85).<br>(2) Grip: grip force decreased for all orthoses.<br>RMS: No difference between elbow positions. No design showed a decrease in RMS as compared to no orthosis. Dorsal orthosis showed increased RMS as compared to volar orthosis suggesting caution with a dorsal design. |
| Hennig 2007 | Determine effects of racket properties on performance and injury in tennis | A series of studies: (1) ball impact, racket vibration, grip force; (2) forehand, backhand, serve; (3) beginner, advanced, expert | Damping qualities of rackets, effect of grip force, ball impact location | Vibration, ball velocity and arm vibration | Stiffer tennis rackets and lower grip forces reduce the mechanical loads on the arm, without impeding ball velocity.<br>Highest vibration with forehand, followed by serve. Beginners hit the ball too close to the hand and experience substantially higher vibrations at the wrist. Experts showed lowest vibration with highest velocity in all 3 types of strokes. |
| Sardelli 2011 | Determine the functional range of elbow motion during contemporary activities of daily living | Repeated measures design<br>N = 24 subjects; 14 male, 11 females | Functional activities: Pouring from a pitcher into a glass, drinking from a glass, eating with a fork, cutting with a knife, reading a magazine, picking up a telephone, standing up from the desk, opening a door, typing on standard computer, using standard mouse, picking up and holding a cell phone to the ear | 10-camera, optical, 3-dimensional motion analyzer to measure degrees of elbow flexion, extension, pronation and supination, and valgus<br>Anthropomorphic: touching vertex head, occiput, chest, neck, sacrum, and shoes<br>Comparison with values reported in the literature (Morrey 1981) | The maximum flexion arc was 130° (minimum flexion of 23° and maximum of 142°) for the cellular telephone task.<br>Maximum pronation-supination arc (103°) using a fork. Maximum pronation, typing on a keyboard (65°). Maximum supination, opening a door (77°).<br>Maximum varus-valgus arc of motion was 11°. Minimum valgus 0° for cutting with a knife, maximum valgus 13° for opening a door. |

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**Table 4** (*continued*)

| Author, year | Purpose | Design/ subjects | Intervention | Measurement | Results/ outcome |
|---|---|---|---|---|---|
| Rossi 2014 | Quantify the impact of racket grip size on applied handle grip and wrist extensor muscle forces. | Repeated measures design: grip handles 3 sizes; fatigue-no fatigue<br>Experimental ball hitting set up<br>N = 8 healthy males | Repeated hitting a ball with the same rackets with 3 types of handles, ranging from small to large | Applied grip on handle measured with by pressure sensors<br>Kinetics modeling<br>Muscle force based on applied grip force and kinematic modeling | Wrist extensors were highly active during the forehand stroke.<br>Non-fatigued speed was higher compared to fatigued condition.<br>The medium-sized racket showed significantly lower muscle force in ECRB and extensor carpi radialis longus; highest ECRB force with the lowest speed with the large handle. |
| Lin 2015 | Determine the effects of position changes and virtual keyboard design on self-reported body discomfort, perceived usability, and postures of the wrist, elbow, and neck during a prolonged tablet typing task. | Randomized design 3 usage positions: desk, lap (seated with keyboard on lap), or bed (seated on bed with keyboard on lap 4 virtual keyboard designs: standard, wide, split, and angled<br>N = 18 (9 males, 9 females) | Desk: upright sitting posture with the tablet placed on top of a 74-cm high desk<br>Lap: a height-adjustable chair with their backs against the backrest, thighs horizontal, and the tablet on their laps<br>Bed: a recliner with knees bent, upper torso supported, and the tablet on participant thighs | System usability scale; electrogoniometry<br>Body discomfort (0-10) of wrists, forearms, shoulders, neck, upper and lower back, and buttocks | Effect of position: highest wrist extension with the bed condition, lowest with desk condition<br>Split design reduced wrist ulnar deviation the most, but increased radial deviation the most<br>The traditional desk setting received the lowest discomfort rating.<br>Body discomforts significantly increased with time in upper extremities, neck, upper and lower backs, and buttocks |
| Buchanan et al. 2016 | To investigate if use of shock-absorbing features to a hammer handle enhances hammer efficiency and reduces forearm grip force and discomfort, and post-hammering wrist extensor edema | Mixed study design: 3 types of handle (wood, steel, or shock control)<br>Tested before, immediately after, and 1-2 days after testing<br>N= 50 healthy subjects randomly assigned type of handle<br>Confirmation of protocol: hammering tasks lead to fatigue for all subjects, as measured by EMG | Repetitively hammering 20 nails into Douglas fir wood, adjusted to allow 90° angle of elbow flexion when hammer head first strikes<br>Shock-absorbing hammer handle allows a very small amount of movement to attenuate shock transmission to the handle | Self-report: discomfort scale 0-10<br>High-speed video: kinetic energy, power of impact, velocity in pixels, EMG wrist extensors, magnetic resonance imaging | Shock-control hammer group had less proximal extensor edema than wood or steel hammer groups<br>Efficiency: shock control hammer had greatest kinetic energy and power on impact<br>No difference in required grip force between hammers, but experienced subjects exerted more force and had less discomfort than inexperienced subjects |
| Ratzlaff 2018 | To evaluate efficacy of an ergonomics intervention to improve lamp positioning in ophthalmology residents | Prospective pilot study; repeated design, 2 weeks follow-up<br>N = 10 ophthalmology residents performing lamp examination and adjustment to a standardized patient | Educational module for best ergonomic practices and injury prevention, developed by interprofessional collaboration (occupational and physical therapists, kinesiologists) | Rapid Upper Limb Assessment injury risk score (from 0 = no risk to 7 = high risk), usability survey<br>Video recording and photographs, joint reaction forces and moments at the right elbow and shoulder, spinal curvature magnitudes, neck and trunk flexion angles | The average Rapid Upper Limb Assessment score improved significantly after educational module.<br>Shoulder forward flexion decreased, elbow winging to the side decreased.<br>Photograph: case changed elbow extension/pronation and wrist extension, to increased elbow flexion, neutral pronation<br>Ophthalmology residents expressed value of the information. |

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**Table 4** (*continued*)

| Author, year | Purpose | Design/ subjects | Intervention | Measurement | Results/ outcome |
|---|---|---|---|---|---|
| **Stage 1: Intervention generation, refinement, modification, and adaptation and pilot testing** | | | | | |
| Chatterjee 1992 | Goal: set up a strategy for the prevention of upper limb disorders<br>Aims: (1) investigate possible occupational and non-occupational factors for association with upper limb disorders, (2) assess the effects of interventions to be used in further investigations | Prospective longitudinal study from 1980-1988<br>All manual workers from 3 departments performing assembly of electronic and small car parts<br>N = 695 (274 males, 412 females) | Multidisciplinary approach, (1) educating supervisors, engineers, occupational health and safety personnel; (2) occupational health: based on worker and job assessment, job restriction, and, if needed, referral to general physician; (3) engineering taskforce for design changes; (4) organizational: planning and implementation | Worker: health surveillance, incidence rates, standardized time and motion studies<br>Ergonomic study: anthropomorphic man model study, incorporating range of motion and postures<br>Tasks: video recordings, photography of tasks and work stations<br>Tools: tool vibration | Worker: affected 85.2% female, 14.8% males, 68% right side, 19% left side, 35 of 88 shoulder, 21 of 88 elbow (19 lateral epicondylitis, 2 medial epicondylitis), 19 of 88 wrist, 13 of 88 fingers 51.1% could not return to the same job<br>Tool: intolerance to vibration still present after 4 Y, especially for women<br>Ergonomic factors: poor seating, reaching, postures, and bad tool design<br>Interventions: decreased incidence rate of LE from 2.1 to 0.1 |
| Smith 2001 | Demonstrate the impact of a concern by one worker to raise awareness of departmental problems, leading to general packaging improvements made by the supplier of seals of vacutainer needles | Case report<br>A phlebotomist with LE due to forceful gripping and repetitive twisting of seal on vacutainer needles | Rest: temporary rest from job<br>Assistive device: an ergonomic long lever device to support breaking the seal is given<br>Organizational: added work breaks and increase in staff<br>Communication with manufacturer | No real measurements<br>Return to work, return to hobbies<br>After 1 year, altered packaging of the product was implemented. | No recurrence of worker's LE. She continues to work and play badminton.<br>Early detection of occupation as a problem may save cost of medical and physical therapy services. |
| McCormack 2009 | To document how ergonomic and behavioral changes as a first line of intervention impact client's symptoms from work-related LE | Case report<br>Female with right LE<br>Comorbidities: epilepsy, status post right shoulder surgery, right ganglion cyst removal, headaches. Failed cortisone injection and failed physical therapy. Recent job change with increased computer work.<br>2 wk follow-up | Work station: keyboard tray<br>Adjustments: mouse, lighting, fiber mat to enhance traction for the wheels of work chair<br>Patient education: neutral positioning and work pacing.<br>Hourly: stretch wrist extensors/flexors, mini rests throughout the day | Ergonomic examination: work station seating, desk specifics, lighting, seat on uneven flooring, reaching excessively during computer work, frequency and duration of activity<br>Physical examination: vision, pain, palpation, manual muscle strength, grip strength, presence of headaches, LE and medial epicondylitis, diagnostic tests, qualitative comments | Diagnostic: case moved from positive LE to negative LE<br>Clinical outcomes: Pre-post worst pain 4 of 10 to 8 of 10, manual muscle strength $4^{+}$ to 5, grip R 42 to 28, L 51 to 62<br>Personal qualitative: improved lighting resulted in decreased headaches, no increase in pain with typing and mouse use after adjustment to keyboard and mouse |
| Parimalam 2012 | To demonstrate the conduct and outcomes of a participatory design process and implementation of dyeing tub design alteration (for textiles) | Repeated measures design, with 2 mo follow-up, measured through the total workday cycle (start, late morning, after lunch, end of the day)<br>Over a group of businesses, 200 workers | Interaction with workers to alter design, interaction between designers and workers to judge the quality of the prototype to fulfil the desired design<br>Tub design alteration<br>Outcomes measurement | Patient-reported measures: standardized measurement, global discomfort, discomfort at most affected physical location (included upper and lower arm pain, not elbow)<br>Dying tub measurements and function<br>Productivity<br>Clear illustrations | Discomfort increased from start to lunch time, lowered over lunch, and increased again up to the end of the shift.<br>After tub implementation: discomfort decreased significantly; highest improvements at the end of the shift, for all body parts except palm of the hand.<br>Low back and hips remained most uncomfortable areas Illustration inadequacy of tub design to protect lower back posture: remaining flexed lower back with tub alteration<br>Production increased 17% |

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| Author, year | Purpose | Design/ subjects | Intervention | Measurement | Results/ outcome |
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| Harari 2019 | Examine the effectiveness of 22-mo multifaceted physical therapist-guided workplace program: (1) participatory ergonomics, (2) workplace exercises, (3) acupuncture on complaints of musculoskeletal disorders, and (4) self-reported absenteeism<br>Hypotheses also included that workers without pain would remain pain-free | Repeated measures design, baseline and post-treatment (22 mo), all subjects eligible to receive the entire program<br>Subjects: N = 126; industry, logistics, 3 groups of office workers<br>All interventions guided by a physical therapist<br>Data collection conducted through surveys online (not taken by the therapist) | Participatory ergonomics: identification of workspace challenges, work task analysis for physical and mental overload, solution building, environmental modifications<br>Group workplace exercises 1x/week for 15 minutes: shoulder rotational exercises, isometric-resistive exercises, balancing exercises, active and passive stretching, and posture education<br>Acupuncture by physical therapist to treat pain, combined with exercises<br>Referral to physician if needed | Muscle pain or discomfort: Nordic musculoskeletal questionnaire, workers' self-perception questionnaire<br>Occupational factors/ life habits relevant to musculoskeletal conditions questionnaire | Worker-reported changes: 85% to 94% improvement in musculoskeletal pain on the workers' self-perception questionnaire (elbow pain decreased in intensity, frequency, and duration [$P < 0.0005$])<br>More energetic after workplace exercises, more comfort in work-related activities<br>Increased productivity (71%) due to decreased pain or discomfort<br>All 12 subjects with pre-intervention elbow/forearm pain reported no pain post-intervention.<br>There was a significant decrease ($P = .020$) in lost workdays due to musculoskeletal pain compared to the previous year. |
| **Stage II: Traditional efficacy testing** | | | | | |
| Sundstrup 2014 | Compare effects of participatory ergonomics programs and strength training, on pain and work disability in slaughterhouse workers with chronic pain<br>Proposal with preliminary results | Single-blind, randomized controlled trial: 10-wk intervention of strength training versus ergonomics<br>Subjects: N = 66 slaughterhouse workers with chronic pain in shoulder, elbow, hands, who self-selected to participate | Strength training: high-intensity strength training of the shoulder, arm, and hand for 3x 10 min a week, 8 resistance exercises with progressive intensity<br>Ergonomics group received counseling on workstation adjustment, optimal use of work tools, and hazard prevention. | Pain intensity, tenderness on palpation, maximal muscle strength of arm and hand, function of arm and hand, Disability of the Arm, Shoulder, and Hand questionnaire | Pain decreased more in the exercise versus the ergonomics group in the shoulder, elbows and hand/wrists. The DASH scores increased in the ergonomics group, but decreased in the strengthening group.<br>Number of subjects with improved results were significantly higher in the exercise group as compared to the ergonomics group.<br>Results can be generalized to adults with upper limb chronic pain exposed to highly repetitive and forceful manual work |
| Soler-Font 2019 | Compare effects of 3 types of prevention interventions on pain and work functioning between nursing and control group | Prospective cluster, randomized control, repeated design; baseline 6 and 12 months follow-up<br>Subjects: nursing staff (n = 246) vs control (n = 133) | Interventions phased: (1) participatory ergonomics, (2) Nordic walking, (3) healthy diet, (4) mindfulness, (5) case management program<br>Both groups received customary occupational therapy. | Self-perceived musculoskeletal pain, sick leave<br>Work functioning: work role functioning questionnaire (Spanish version) | Global musculoskeletal pain decreased, also in elbows (odds ratio, 2.02).<br>Results suggest that a multifactorial approach is needed, including multiple levels of prevention. |
| **Stage III: Efficacy testing with real-world providers** | | | | | |
| Haahr and Andersen 2003 | Investigate the benefits of an instructional program provide by an occupational physician, including exercise and ergonomics, compared to standard medical management | Repeated measurements design; follow-up at 3, 6, and 12 mo<br>Randomization, with independent outcome measurement<br>Baseline: intervention, n = 148; control, n = 141 | Information about LE, including that it was self-limiting<br>Advise against complete rest, but avoid painful activities<br>Adjust work conditions when possible<br>One visit with an ergonomist who instructed in graded exercises | Direction of pain (improved or not)<br>Provided treatments, number of visits with a physical therapist or general practitioner<br>Sickness absence | Intervention vs control<br>Provide treatments: less applied personally directed exercise, lower number of modalities received, no difference in number of visits to physical therapist or general practitioner<br>Pain decreased and proportion improved in both groups equally.<br>No difference between groups in sickness absence |

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| Author, year | Purpose | Design/ subjects | Intervention | Measurement | Results/ outcome |
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| Nilsson et al. 2012 | To examine outcomes of a structured 1-provider program for patients with LE in comparison to a non-standardized treatment program applied by external practitioners | Prospective post-test-only design (after 2 Y)<br>Patient-Rated Forearm Evaluation Questionnaire sent by mail; group assignment: blinded intervention group (n = 103), controls (n = 194), treated in the community, living far away from each other to limit contact | Experimental group: occupational and physical therapy intervention, written 15-minute home training program to be performed 3x per day over 4 mo; non-specified ergonomic advice for work and home<br>Control group: non-standardized care by varying healthcare professionals | Patient-Rated Forearm Evaluation Questionnaire, pain, function, rate of recurrence, sick leave | Applied treatments:<br>Experimental: 31% home exercise program and night bandage, 37% home exercise program and wrist support, 37 home exercise program only<br>Control: 35% NSAID, 31% injection, 34% home exercise program, and/or acupuncture, services provided by various health care professionals<br>Outcomes after 2 Y: intervention group had less pain and function loss, fewer recurrences, with fewer patients on sick leave compared to control group ($P < 0.005$)<br>Structured program by singular clinic found to be more effective than primarily corticosteroids or NSAID program offered by a variety of practitioners |
| **Stage IV: Effectiveness research** | | | | | |
| Heidarimo-ghadam 2020 | Examine whether ergonomic interventions make a difference in workplace settings | Systematic review<br>High-quality articles<br>Comprehensive, resulting in 22 studies included the qualitative synthesis | Ergonomic interventions | Body discomfort, musculoskeletal pain, discomfort or strain, cost-effective analysis, psychosocial workload, physical workload, sick leave, lower back pain, general health, posture assessment, workability, productivity | Workplace improvements correspond with a significant reduction of upper limb musculoskeletal disorders.<br>Feedback interventions, participatory ergonomics, and job rotations with ergonomic guidance did not significantly influence risk of psychosocial factors.<br>Workplace improvements and job rotations with ergonomic guidance did not significantly improve productivity. |
| Sundstrup 2020 | Systematic review to investigate effectiveness of workplace interventions for workers with demanding jobs, specified to LE | Randomized studies: ergonomic intervention and exercise<br>Inclusion: adult workers with pain, workplace<br>73 studies (including 54 unique workplace interventions) | Workplace interventions: strengthening, ergonomics, multifaceted | Pain, symptoms, prevalence or discomfort<br>Defined levels of evidence, not including review evidence | Strong evidence to support workplace strength training<br>No evidence to support multifaceted programs<br>Strong evidence of no benefit for ergonomics<br>Insufficient evidence to guide current ergonomic programs |

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| Author, year | Purpose | Design/ subjects | Intervention | Measurement | Results/ outcome |
|---|---|---|---|---|---|
| **Stage V: Dissemination and implementation research** | | | | | |
| Koningsveld et al. 2005 | Identify successful factors for designing ergonomic programs for ergonomists involved in project design and evaluation | Invited plenary paper, review illustrated with 12 demonstration cases 12 different work programs and work situations, machine construction workers, street car drivers, home care workers<br>All projects included upper extremity work<br>Programs: 6 participatory, 6 non-participatory | Process: assessment, implementation, effect measurement<br>Interventions: machine and workplace improvements to fit with the worker<br>Hand-tool improvement<br>Office designs | Measurements among the 12 cases: time and motion studies, assessment of physical loads<br>Structured interviews, questionnaires<br>Absenteeism rate, number of employed staff and personnel turnover<br>Excellent illustrations of workers in an activity representative for the job | Design recommendations: (1) inventory of problems, (2) worker participation, (3) management support, (4) step-by-step approach, (5) expand focus beyond health issues, (6) establish steering group, (7) check program effects, (8) check the cost/benefit ratio<br>Worker outcomes: participatory programs excelled in physical and productivity outcomes<br>Worker satisfaction and health taken seriously by management were similar between ergonomic approaches |
| Gyi et al. 2013 | To show a demonstration model of utilizing a participatory ergonomics process | 17 organizations with a cohort of more than 500 drivers, driving > 15,000 miles per year, or more than 4 H per day<br>Manufacturing, utilities, pharmaceuticals, consultancy | Participatory process with 4-phase participant and researcher model of design, implementation, and outcome measurement | 3 sources of data: (1) interviews, research diaries, car dimensions, driving-related behavior (ex: working from the car); (2) Nordic musculoskeletal questionnaire, job satisfaction questionnaire, 12-item General Health Questionnaire, Intention to Leave Scale 3, Organizational Commitment Scale | Participant attrition was a problem in a longitudinal approach.<br>Participants were often not aware of the "train-the-trainer program." But when aware, the "train-the-trainer" program raised awareness of the risks to musculoskeletal health of the daily activities of drivers when working in their vehicles, such as using the car as an office and/or manual handling from the car.<br>Managers had increased awareness of workers' risks for musculoskeletal problems.<br>The program was successful in implementing changes. |

ECRB = extensor carpi radialis brevis, EMG = electromyography, NSAID = non-steroidal anti-inflammatory drug, RMS = root mean square, LE = lateral epondylosis

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## Quiz: # 762

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# 1. The study design was
  a. RCTs
  b. case series
  c. integrative review
  d. qualitative

# 2. In addition to tissue-specific interventions, the authors strongly recommend
  a. activity analysis and modification
  b. mobilization with movement
  c. pulsed ultrasound
  d. enforced rest from function

# 3. Tendinosis has been shown to be the caused by repetitive cyclic loading through
  a. videography
  b. computer modeling
  c. controlled human subjects studies
  d. laboratory studies on rats

# 4. Their investigation identified ___________ as a possible source of pathology in addition to the traditional extensor tendons
  a. ulno-humeral ganglion
  b. superficial branch of the radial sensory nerve
  c. enthesis of the capitellum
  d. lateral aspect of the radial head

# 5. The authors encourage further investigation into parameters of ergonomic intervention
  a. not true
  b. true

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