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A Theoretical Framework for Understanding Neuromuscular Response to Lower Extremity Joint Injury

Brian G. Pietrosimone, PhD, ATC,* Michelle M. McLeod, MA, ATC, and Adam S. Lepley, MA, ATC

Background: Neuromuscular alterations are common following lower extremity joint injury and often lead to decreased function and disability. These neuromuscular alterations manifest in inhibition or abnormal facilitation of the uninjured musculature surrounding an injured joint. Unfortunately, these neural alterations are poorly understood, which may affect clinical recognition and treatment of these injuries. Understanding how these neural alterations affect physical function may be important for proper clinical management of lower extremity joint injuries.

Methods: Pertinent articles focusing on neuromuscular consequences and treatment of knee and ankle injuries were collected from peer-reviewed sources available on the Web of Science and Medline databases from 1975 through 2010. A theoretical model to illustrate potential relationships between neural alterations and clinical impairments was constructed from the current literature.

Results: Lower extremity joint injury affects upstream cortical and spinal reflexive excitability pathways as well as downstream muscle function and overall physical performance. Treatment targeting the central nervous system provides an alternate means of treating joint injury that may be effective for patients with neuromuscular alterations.

Conclusions: Disability is common following joint injury. There is mounting evidence that alterations in the central nervous system may relate to clinical changes in biomechanics that may predispose patients to further injury, and novel clinical interventions that target neural alterations may improve therapeutic outcomes.

Keywords: neuromuscular; knee; ankle; lower extremity; injury

Disability is common following joint injury and/or surgery, including anterior cruciate ligament ruptures and reconstructions,[3,43,49,67,76] meniscectomy,[71] osteoarthritis,[15,72] total knee arthroplasties,[4,32] acute ankle sprain,[8] and chronic ankle instability.[16,45] Neuromuscular alterations following ankle and knee injuries may play a role in altering functional performance, potentially contributing to disability in different populations.[12,55]

Neuromuscular alterations following joint injury represent complex clinical impairment that can manifest as inhibition[53,54] or abnormal facilitation[53] of uninjured musculature surrounding an injured joint. This neural response likely has 2 major physiologic purposes: (1) decreasing excessive loads around an injured joint to protect against further injury[30] and (2) providing compensatory motor strategies for ambulation and maintenance of upright stance in the presence of muscle inhibition.[22] Joint protection and the ability to generate compensatory movements are both important acute responses to lower extremity joint injury. Interestingly, some people never regain preinjury neuromuscular function,[80] which leads to prolonged alterations in neuromuscular muscle function and extremity movement.[18] These changes in neuromuscular function contribute to altered biomechanics, which may be an important factor in long-term functional outcomes following lower extremity joint injury.[55,58,66] While neuromuscular alterations can occur at any joint in the body, this review focuses on neuromuscular alterations surrounding the knee and ankle joints.

CURRENT HYPOTHESES REGARDING NEURAL ALTERATIONS TO JOINT INJURY

Neural alterations following joint injury are likely a result of micro- or macrotrauma to joint structures.[9,25,78] The joint injury or effusion excites a variety of receptors, including pacinian corpuscles,

From the Joint Injury and Muscle Activation Laboratory, Department of Kinesiology, University of Toledo, Toledo, Ohio *Address correspondence to Brian G. Pietrosimone, PhD, ATC, Department of Kinesiology, Joint Injury and Muscle Activation Laboratory, College of Health Science and Human Services, University of Toledo, MS 119, 2801 West Bancroft Street, Toledo, OH 43606-3390 (e-mail: brian.bietrosimone@utoledo.edu).

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Ruffini fibers, Golgi tendon organs, and free nerve endings, which are located in and around human joints.[33] These receptors relay sensory information from joints to the central nervous system.[33] The neuromuscular dysfunction of the uninjured musculature surrounding an injured joint may be a result of arthrogenic muscle response[53,54]: a protective mechanism used to manage forces around the injured joint. These neuromuscular alterations may be resistive to traditional therapy[29,61] and a factor in the development of further joint degeneration.[55]

The contributions of pain to neuromuscular responses to joint injury are not fully understood.[20,47,62] Both pain and mechanoreceptor function alter muscle excitability.[25] Joint pain can modify muscle function independently of joint injury,[20] and joint effusion seems to alter muscle function independently of pain.[22,54] Quadriceps muscle function during stair ascent has been affected by knee pain induced by a hypertonic saline injection into knee joints of healthy participants.[20] This suggests that pain can alter muscle function without injury. In contrast, decreased quadriceps spinal reflexive excitability[21,22,53,54] and altered neuromuscular control[57,79] have been observed following a nonnoxious knee joint effusion, suggesting that inhibition can be initiated independent of pain. Artificial joint effusions that generate very little pain can cause a significant neuromuscular response at the knee[53,54] and ankle.[53] Additionally, following intervention, changes in muscle activation and pain occur independent of each other,[62] suggesting that these clinical impairments may be initiated by different neural pathways.

NEUROMUSCULAR ALTERATIONS FOLLOWING JOINT INJURY AND THE POTENTIAL IMPACT ON PHYSICAL FUNCTION AND DISABILITY

Central Nervous System Pathways

Movement relies on 2 major nervous system pathways: spinal reflexes and voluntary excitation descending from the motor cortex.[33,70] The function of these neural pathways dictates the ability of muscles to contract in the periphery.

Spinal Reflex Pathway

Spinal reflexes can be studied with a joint effusion model.[22,24,26,52-54] Simulated effusion of the knee joint causes almost immediate decreases in quadriceps spinal reflexive excitability.[22,24,26,53,54] Inhibitory mechanisms can influence sensory signals in the central nervous system via pre- or postsynaptic inhibition.[53,54] Presynaptic inhibition helps control movement,[33] through the modulation of the afferent signal by using a third neuron that decreases neurotransmitter released by afferent nerves synapsing on interneurons in the central nervous system.[28,54] The amplitude of the excitatory postsynaptic potentials correlates with the amount of presynaptic inhibition.[28] Conversely, postsynaptic inhibition is in part modulated by Renshaw cells, responsible for decreasing activation of involved alpha motor neurons.[28]

Gamma (γ) motor neuron deficits following injury may indirectly affect muscle activation.[37-39] The γ motor neuron system regulates the length of intrafusal muscle spinal fibers and functionally dictates the sensitivity of the stretch reflex.[33] Therefore, desensitized muscle spindles may alter sensory signals propagated to the central nervous system.[39] Diminished quadriceps γ motor system function has been found with anterior cruciate ligament deficits[38] and reconstructions.[37] These γ motor deficits can occur bilaterally following unilateral knee injury.[39]

Ankle joint effusion affects spinal reflexive excitability of the anterior tibialis, fibularis longus, and soleus.[53] Acute lateral ankle sprains (24-72 hours postinjury) produce abnormal facilitation of the soleus and inhibition of the anterior tibialis to position the ankle in plantar flexion.[36] Patients with chronic ankle pathology, such as functional ankle instability, demonstrate decreased soleus and fibularis longus activation.[46]

Cortical Pathways

Transcranial magnetic stimulation (TMS) allows for evaluation of cortical pathways using an exogenous magnetic stimulus applied over cortical neurons to elicit an evoked potential, which is measured with electromyography in the corresponding peripheral muscle.[70] Altered cortical control of the quadriceps has been demonstrated following anterior cruciate ligament injuries[19] and in those with joint pain.[51] Cortical excitability may be upregulated following joint injury in surrounding musculature.[51] While the functional outcome of these alterations remains unknown, it is possible that these increases in cortical excitability may be related to a compensatory neuromuscular strategy used in the presence of a joint injury.

Voluntary Activation and Muscle Strength

Voluntary muscle performance is determined by motor unit recruitment and firing rate, which is potentially influenced by both spinal and cortical pathways.[34,75] These deficits in voluntary quadriceps activation have been found bilaterally following unilateral injury,[60,81] making it difficult to delineate if these neuromuscular alterations are a result of joint injury or a predisposing factor to joint injury. Decreased voluntary quadriceps activation in combination with muscle weakness predicts disability in patients with knee osteoarthritis.[12] Voluntary quadriceps activation deficits are common in patients with acute knee injury[17] or surgery, as well as in patients with chronic knee osteoarthritis.[60]

The relationship between volitional quadriceps activation and strength is complicated. While a positive correlation between voluntary activation and muscle strength exists,[40] muscle atrophy is likely not the sole determinant of strength deficits following joint injury.[59] Strength deficits exist in stabilizing musculature around the ankle[2] and proximal muscles of the hip[13] following lateral ankle sprains. Increased voluntary quadriceps activation in patients with chronic ankle instability

may be caused by neural facilitation due to decreased muscle function around the ankle.

Biomechanical and Functional Performance Changes Related to Neuromuscular Alterations

Compensatory motor strategies may be a product of altered neuromuscular function.[58,79] Artificial knee joint effusions facilitate reflexive excitability of multiple muscle groups, including the hamstrings[79] and soleus musculature,[21] which may have a dramatic influence on functional movement. Decreased knee flexion angles have been found in those with effused knees when landing from a jump.[58] Decreased knee angles during the stance phase of gait[6,42] may be a consequence of the inability of the quadriceps muscles to eccentrically contract. Additionally, external knee flexion moments are decreased during the stance phase of gait in those with knee osteoarthritis.[42] Quadriceps dysfunction following acute knee injury may be a factor in the risk of developing posttraumatic osteoarthritis, as weakness and/or inhibition likely produces irregular force attenuation at the knee joint.[55,65] Additional alterations in performance, specifically balance deficits[1] and gait abnormalities,[11] are common in patients with ankle sprains.

Theoretical Clinical Framework and Potential Limitations

Neuromuscular alterations following joint injury at the knee and ankle are linked to biomechanical or functional deficits present in patients after knee and ankle injury. This model focuses on neural influences and does not take into account factors such as body weight, age, or morphologic changes within the muscle, which may also predict muscle changes.

TREATMENT OPTIONS FOR NEUROMUSCULAR DEFICITS

Resistance training alone may not be sufficient when neuromuscular deficits are present.[27,57] Conventional quadriceps strengthening alone will not increase quadriceps activation in those with activation deficits.[61] Therefore, attempting to traditionally strengthen a muscle may not influence the central nervous system.[62,63] Currently, there seem to be 3 potential points in the nervous system at which therapeutic interventions may be able to target neuromuscular deficits: motor cortex, spinal reflexive pathways, and inhibited muscle.

Increasing Cortical Motor Excitability

Transcranial magnetic stimulation (TMS) can stimulate areas on the motor cortex that consequently excite muscles in the periphery.[70] A single pulse of TMS during a maximal quadriceps contraction superimposes twitches in the knee extensors.[50] TMS can excite the quadriceps beyond voluntary effort after meniscectomies.[14] While TMS shows some potential to improve cortical motor excitability, integrating TMS treatment into clinical practice may be a challenge due to high equipment costs and needed expertise.

Electromyographic biofeedback is used with therapeutic exercise after knee joint injury to target decreasing cortical stimuli.[73] Biofeedback may increase muscular strength and neuromuscular control by improving motor unit recruitment[7,41,44] and/or optimizing firing rates.

Targeting Spinal Reflex Pathways

The goal of modality use is to increase afferent stimuli around the injured joint that can be excitatory to the central nervous system.[62] Excitatory afferent stimuli may increase motor neuron response. Transcutaneous electrical nerve stimulation (TENS) may return quadriceps reflexive excitability to pre-effusion levels[26] and decrease presynaptic inhibition[31] known to modulate arthrogenic muscle responses.[54] This increase in reflexive excitability may activate the quadriceps within a single 45-minute treatment in tibiofemoral osteoarthritis.[62] TENS applied during therapeutic exercise and activities of daily living may improve voluntary muscle activation and strength.[61] These improvements in voluntary activation were sustained following the removal of TENS.[62] TENS is a reasonable intervention option for increasing quadriceps spinal reflexive excitability, voluntary activation, and muscle strength. Walking speed and gait cadence are increased following a 4-week TENS and exercise program.[5] Conversely, TENS and quadriceps strengthening did not alter sagittal plane moments and knee joint angles during gait.[65]

Current clinical guidelines utilize TENS directly over the injured joint, usually around the patella, to minimize contact with adjacent musculature.[63] A continuous strong submotor sensory stimulus over the joint is currently recommended.[26,63] Increased voluntary activation has been seen using a biphasic, pulsatile current (~150 Hz, 150 microseconds) during strength training sessions and activities of daily living (~8 hours per day) over a 4-week period.[61,62]

Joint cooling may increase motor excitability of surrounding musculature by exciting thermoreceptors around the injured joint.[26] Focal knee cooling increases spinal reflexive excitability following artificial knee effusions[26] as well as maximal quadriceps activation in healthy[64] and osteoarthritic patients.[62] Focal ankle cooling increases spinal reflexive excitability and muscle strength in the soleus muscle.[23] In addition, a subsensory random electrical or vibratory stimulus (stochastic resonance therapy) has improved postural control in chronic ankle instability.[68,69]

Stimulating Inhibited Muscle

Neuromuscular electrical stimulation (NMES) has been used to activate inhibited muscle to limit atrophy. This method is significantly different because NMES does not target inhibitory pathways. NMES augments a voluntary contraction, creating an involuntary contraction of inhibited muscle.[48,77] NMES may provoke sustainable change in neural excitability. Muscle strength seems to improve following NMES and exercise, but there are no definitive benefits in functional performance

or self-reported function.[35] A recent study of patients with chronic knee injuries demonstrated no significant difference in quadriceps activation or strength following NMES training compared with traditional strength training.[56]

A recent systematic review[35] of NMES on quadriceps strength following anterior cruciate ligament reconstruction shows strong improvements in strength when the longest phase durations (300-400 microseconds) were used.[10,74,82] The longest "on times" for the duty cycles (15 seconds on, 50 seconds off) demonstrated strong effect sizes despite the shortest treatment durations (4-6 weeks, 12-15 sessions). The majority of studies utilized a maximal tolerable intensity for NMES. However, increasing the lengths of pulse width and "on times" may stimulate greater improvements in muscle strength.

CONCLUSIONS

Neuromuscular deficits following joint injury are common and may affect muscle strength and biomechanics. These clinical impairments may be dictated by underlying spinal reflexive or cortical pathways and can result in abnormal facilitation or inhibition of affected musculature. Inhibition of muscles surrounding an injured joint may be a natural protective mechanism to decrease excessive forces. While compensatory movements may be helpful in completing specific tasks, they may be suboptimal.[58] Traditional therapeutic exercise may not adequately improve strength or muscle activation.[61] The literature demonstrates that development of a new therapeutic paradigm that focuses on restoring proper upstream neural function may have significant effects on downstream neuromuscular control and patient function.

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