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REVIEW

Slacklining as therapy to address non-specific low back pain in the presence of multifidus arthrogenic muscle inhibition

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Abstract

Low back pain (LBP) represents the most prevalent, problematic and painful of musculoskeletal conditions that affects both the individual and society with health and economic concerns. LBP is a heterogeneous condition with multiple diagnoses and causes. In the absence of consensus definitions, partly because of terminology inconsistency, it is further referred to as non-specific LBP (NSLBP). In NSLBP patients, the lumbar multifidus (MF), a key stabilizing muscle, has a depleted role due to recognized myocellular lipid infiltration and wasting, with the potential primary cause hypothesized as arthrogenic muscle inhibition (AMI). This link between AMI and NSLBP continues to gain increasing recognition. To date there is no 'gold standard' or consensus treatment to alleviate symptoms and disability due to NSLBP, though the advocated interventions are numerous, with marked variations in costs and levels of supportive evidence. However, there is consensus that NSLBP management be cost-effective, self-administered, educational, exercise-based, and use multi-modal and multi-disciplinary approaches. An adjuvant therapy fulfilling these consensus criteria is 'slacklining', within an overall rehabilitation program. Slacklining, the neuromechanical action of balance retention on a tightened band, induces strategic indirect-involuntary therapeutic muscle activation exercise incorporating spinal motor control. Though several models have been proposed, understanding slacklining's neuro-motor

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mechanism of action remains incomplete. Slacklining has demonstrated clinical effects to overcome AMI in peripheral joints, particularly the knee, and is reported in clinical case-studies as showing promising results in reducing NSLBP related to MF deficiency induced through AMI (MF-AMI). Therefore, this paper aims to: rationalize why and how adjuvant, slacklining therapeutic exercise may positively affect patients with NSLBP, due to MF-AMI induced depletion of spinal stabilization; considers current understandings and interventions for NSLBP, including the contributing role of MF-AMI; and details the reasons why slacklining could be considered as a potential adjuvant intervention for NSLBP through its indirect-involuntary action. This action is hypothesized to occur through an over-ride or inhibition of central down-regulatory induced muscle insufficiency, present due to AMI. This subsequently allows neuroplasticity, normal neuro-motor sequencing and muscle re-activation, which facilitates innate advantageous spinal stabilization. This in-turn addresses and reduces NSLBP, its concurrent symptoms and functional disability. This process is hypothesized to occur through four neuro-physiological processing pathways: finite neural delay; movement-control phenotypes; inhibition of action and the innate primordial imperative; and accentuated corticospinal drive. Further research is re-commended to investigate these hypotheses and the effect of slacklining as an adjuvant therapy in cohort and control studies of NSLBP populations.

Key Words: Slacklining; Arthrogenic muscle inhibition; Low back pain; Therapy-intervention; Multifidus; Hypothesis

Core Tip: Non-specific low back pain (NSLBP) is the leading problematic musculo-skeletal condition for individuals and society. With no consensus definition, depleted lumbar multifidus stabilization is recognized with fatty infiltration and wasting, where arthrogenic muscle inhibition is a probable cause. With no gold-standard therapy, management consensus recommends cost-effective, self-administered, exercise-based multi-modal approaches. 'Slacklining' addresses these criteria as an adjuvant therapeutic rehabilitation exercise, rationalized by a hypothesized over-ride of central down-regulatory induced muscle insufficiency. This allows neuroplasticity, normalized neuro-motor sequencing and muscle re-activation for stabilization. Four neuro-physiological pathways are proposed with further research required into the hypotheses and slacklining's potential NSLBP rehabilitation role.

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INTRODUCTION

Low back pain (LBP) is a major global health and economic concern due to its prevalence, heterogeneous classification and multiple causes and diagnoses. It affects more individuals than any other musculoskeletal condition[1], but is mostly 'non-specific' (approximately 85%), as the source of abnormality and symptoms is undefined[2]. Non-specific LBP (NSLBP) is characterized by factors that cross biophysical, psychological and social domains, and presents on a spectrum from neuropathic to nociceptive pain[3]. The neuropathic component is predominantly from nerve root compression within or adjacent the spinal canal from several potential causes, whereas nociceptive is associated with mechanical stress[4] and non-neural tissue damage[5,6]. This leads to broad problems for the individual's function, ability, activities of daily living (ADL), societal participation, and economic situation. There are also societal demands on health-care and support networks, that vary considerably within and between countries, due to local approaches, social attitudes, and legislative influences[1,2]. The most widely used categorization of NSLBP is acute (< 6 wk), subacute (6-12 wk), or chronic (> 12 wk), causing symptoms in > 50% of days[3,7,8].

However, there is no ‘gold standard’ management that demonstrates a strong, cost efficient, evidence-based effect[2]. This is partly because consensus is divided on the terminology used and the approaches advocated. Different terms such as mechanical or axial LBP refer to the same condition, causing inconsistency in nomenclature due to varied interpretations by clinicians, researchers, and society in general; while the many diverse and conflicting approaches and interventions recommended perpetuate the perplexity[6]. Systematic reviews and meta-analyses indicate the different interventions show markedly varied levels of cost efficiency and supportive evidence, both between and within approaches[2]. One area with general agreement is that spinal stability[9-11] is critically important, particularly at the segmental level[12,13] where the abdominal and lumbar muscles[6] contribute significantly[14,15], with the multifidus (MF) muscle having a strategic functional role[12]. Accordingly, any condition that disrupts and compromises this lumbo-pelvic stabilization capacity, such as myocellular lipid (MCL) infiltration and wasting leading to depletion of the MF stabilizing role, should be investigated and addressed[6,16,17].

One such causative condition is arthrogenic muscle inhibition (AMI)[17-22], which is summarily defined as “… a neural activation deficit [of the muscles]”[23] (see Supplementary material, Appendices 1-3. Consequently, AMI has gained increasing recognition and research interest over recent decades as a primary contributor to NSLBP[5,6,17]. Therefore, intervention techniques that address MF deficiency induced through AMI (MF-AMI), use direct/indirect muscle activation approaches that target the MF through voluntary/involuntary activation, and are clinically important[24], particularly if they are self-directed, and cost effective[13,15].

Within this clinical framework of self-directed, cost effective interventions addressing MF deficiency, any new techniques are encouraged[15]; with a very recent paradigm being indirect-involuntary muscle activation, where slacklining is a specific example. Slacklining, ‘the neuromechanical action of balance retention while standing on a tightened webbing band’[25-28], has been introduced over recent decades as a strategic musculoskeletal and neurological therapeutic pre- and re-habilitation exercise[29,30]. However, published slacklining research is recent and available evidence remains limited[31-33], particularly for clinical rehabilitation implications[30,34-36], and formulated explanatory models[28,31], despite slacklining’s ancient origins[37]. Slacklining invokes a moderated indirect muscle activation that occurs involuntarily and facilitates achieving optimum balance according to the needs of the motor task through muscle, joint, and subsequent limb and body control[31,38]. It has been clinically demonstrated to overcome AMI during rehabilitation in peripheral regions and joints, particularly the knee and ankle[23,30,39], and is recently reported as potentially showing promising clinical results in reducing MF-AMI induced NSLBP[17].

Consequently, this paper aims to rationalize why and how slacklining, as an adjuvant therapeutic exercise, may positively affect patients with NSLBP that is due to MF-AMI induced depletion of spinal stabilization. We consider slacklining’s centrally mediated pre-synaptic actions that provide either an over-ride or inhibition of the down-regulatory induced MF insufficiency that occurs as a consequence of AMI. This action will, consequently, allow neuroplasticity, the restoration of normal neuro-motor sequencing that enables MF re-activation, subsequent spinal stabilization, and the resultant improvement in symptoms and function. This in-turn addresses and reduces NSLBP and its concurrent symptoms and functional disability.

This action is hypothesized to occur through one or a combination of four neurophysiological processes that occur within the following pathways: (1) Finite neural delay accompanying ‘time available’ processing; (2) Movement control phenotypes affected by an exercise reasoning hypothesis; (3) The inhibition of action and the innate primordial imperative; and (4) Accentuated corticospinal drive. To comprehend these actions and understand their implications requires a step-wise rationalization that involves a process of: presenting a summary review of NSLBP and spinal stability; the MF stabilizing role; how AMI depletes this stabilization; recognized NSLBP rehabilitation methods; slacklining as an adjuvant therapeutic exercise; and, subsequently, slacklining’s neuro-physiological effects of centrally mediated pre-synaptic actions that provide either an over-ride or inhibition of the down-regulatory induced MF, that counter the local stabilization inadequacies that result in NSLBP.

NSLBP AND SPINAL STABILITY

The classic Panjabi spine-stability model[9,10] hypothesizes that NSLBP originates from the embedded mechanoreceptors of passive spinal support structures (ligaments, disc-annulus, and facet-capsules), which are subject to large-singular or cumulative-micro trauma causing sub-failure injuries. This model was initially amended to include the thoracolumbar fascia[40], then further adapted to integrate mobility[11]. The injury-affected structures generate corrupted transducer signals that alter the neuromuscular control units response patterns, which disrupts muscular onset-shutoff coordination and force magnitude characteristics[6,9,10]. Lumbar spine vertebral joints are over-loaded[4] from 'functional instability' due to 'motor-control system anomalies'[9,11,16]. These are both a cause and effect of neuroplastic changes in sensorimotor control[41-43] and impaired lumbar MF corticomotor control[6,44]. Addressing these factors involves muscle activation, such as 'motor control exercises' (MCE) at the local and or global level, which aim to restore coordinated and efficient use of the muscles that control and support the spine[13,45]. These target the 'core' stabilizing muscles, transversus abdominus (TrA), erector spinae (ES), pelvic floor (PF), and MF[6,46]; however, only MF provides segmental stability[12,13].

The use of MCE therapy aims to restore muscle activation to the disrupted MF, either alone or in combination with the other core muscles[6,46], though with conflicting available evidence[47,48]. Systematic reviews of characteristic macroscopic structural MF changes in NSLBP patients indicate "… a loss of muscle size … [especially] in the lower lumbar levels …"[49]; and distinct differences in muscle size and levels of fat infiltration compared to age and gender related norms[12,50,51]. However, correlation of these changes with clinical outcome improvement varies[48], as supportive evidence is low-moderate in higher quality studies[16,47], while lower quality studies overestimate MCE effectiveness[45]. Consequently, MCE can be considered as supported, but without a unified consensus approach[13].

LUMBAR MF ROLE IN SPINAL STABILIZATION

Researching trunk muscles structure, particularly MF, and their contributions to spinal stability and the clinical association with NSLBP, has continued for over 50 years[45]. The MF has a specific segmental stability role[10-12], and is the muscle with the strongest influence on lumbar stability against applied forces, especially in flexion and extension[12,13], the two predominant motor control impairment clinical directional subgroup classifications[52,53]. A lack of adequate segmental stability results in abnormal stress on ligaments, muscles, and mechanoreceptors; which leads to excessive facet joint loading[10,13]. Since spinal ligaments have inherently poor healing, disc and facet joint degeneration accelerates. Persistence of such abnormal conditions results in NSLBP from: neural tissue inflammation, changes to biochemistry, nutrition, stem cells immune factors, endplate structure and composition, discs, and neural tissues with ingrowth into the intervertebral discs[10]. In this situation, the MF's stabilizing role is depleted and hypothesized as due to AMI[5,6,17]; with supportive evidence from MCE therapy[13,14,24,45,54], and the effects of localized neuromuscular electrical stimulation (NMES) which directly induces involuntary episodic MF-contraction[5,6,16,55].

The links between NSLBP, lumbar muscle wasting, and fatty infiltration by macroscopic MCLs was recognized over 25 years ago[12,14], though there has been both subsequent support for the model, and questioning of whether these links have consistent correlations[49]. The attribution of this lumbar MF wasting to AMI was first speculated in 2002[56], while acceptance of AMIs contribution to NSLBP is only quite recent[5,6,16]. Recognizing MF-AMI is a clinical diagnosis, but supported by physical measures of wasting on ultrasound (US) imaging[44], and MCL infiltrates on dual/multi-echo magnetic resonance imaging (MRI) and MR-spectroscopy[51]. The latter also provides muscular-MCL composition and distinguishes between extra-MCLs (EMCLs), associated with age-related change, and intra-MCLs (IMCLs) associated with NSLBP[17,51]. Consequently, IMCLs and changes in their percentage presence may enable: the described diagnostic techniques to function as a proxy for MF-AMI induced NSLBP; and act as prognostic markers for the efficacy of NSLBP rehabilitation management techniques directed at MF activation/stimulation for spinal stabilization[6,17].

ARTHROGENIC MUSCLES INHIBITION — CURRENT CONCEPTS

The introductions summary definition of AMI as "… a neural activation deficit [of the muscles]"[23], can be further expanded and detailed through the current descriptive consensus of: Periarticular muscle inhibition, often with associated atrophy, from modulation of motor neuron pools within the uninjured muscle/s, that prevents voluntary recruitment about a damaged or distended joint[21,57], and may include the contralateral unaffected side[23]; where motor insufficiency and activation failure is a consequence of a presynaptic reflex reaction through neural inhibition and ongoing neural activation deficit of the muscles, due to compromised efferent drive in the local, spinal and supra-spinal pathways, resulting from aberrant afferent discharge from joint mechano-sensory receptors, which serves as a natural response to protect from further damage[18-23,57-60].

The distinction of AMI from 'disuse atrophy', which has no central nervous system (CNS) or reflex basis[58], has been made since Hippocrates around 400BC[61]. However, the specific mechanism eliciting and controlling AMI remains unclear in all recent publications[22,62], and has predominantly been postulated from the recognized actions and effects following knee joint injury[6,23]. Consequently, though the physiological neuro-motor basis of AMI remains poorly understood, significant investigation continues, particularly research into the cerebral-based mechanisms of AMI[22,63].

Clinically AMI results in an inability to completely activate the periarticular muscles as the available volume of motor units is reduced[20,21]. This leads to a 'vicious circle'[19] of atrophy, weakness, damage, and dysfunction[59]. Consequently, AMI is consistent across different joints and joint pathologies throughout the body, and often most severe in the acute stage of joint damage[21]. The level of afferent discharge from changes in the articular sensory receptors is determined by several factors. Consequently, the mechanisms that drive the severity of AMI presentation are: the severity of the damage to the joint, distention due to inflammation and effusion, joint laxity[6,20,23], the angular position of the affected joint/s, and time-duration since the injury[21]. These factors, subsequently, initiate changes at all levels of the CNS[21], and is expanded on below and in Supplementary material, Appendix 2.

AMI — neurophysiology of AMI actions within the CNS

The mechanisms of action for AMI initiated by neural pathways at the local/ peripheral, spinal, and supra-spinal/central levels of the CNS are summarized as follows.

Local/peripheral level changes: These are a consequence of sustained tissue damage that alters muscle resting motor thresholds, and articular sensory receptor afferent discharge[6,19,20,58,64]. These predominantly include loss or irregularity of the affected articular sensory receptors themselves, joint laxity, and joint damage from distention due to swelling and/or inflammation[21].

For articular sensory receptors, the degree of joint structural trauma affects the level of damaged local nerve endings, with decreases in afferent output when the sensory endings are damaged[59,65], but increases with distention and joint laxity, which accounts for the strong association with AMI[21]. With joint laxity there is altered sensory receptor activation. The presence of structural damage, and/or degenerative change, enables increased intra-articular movement and joint surface translation, which increases mechanoreceptor and nociceptor activation. This in-turn signals the joints range of movement limits. Consequently, anomalous sensory receptor firing during joint movement will be present.

With joint distention from swelling, including clinically undetectable effusions, intra-articular pressure (IAP) is raised. This increases Group II afferent discharge from the joint through stimulation of pressure sensitive and stretch mechanoreceptors. This strongly inhibits the periarticular muscles, as the Group-I non-reciprocal (Ib) inhibitory interneurons in the spinal cord in-turn inhibit localized muscle α-motoneurons, which prevents full muscle activation. This results in significant AMI, as shown directly in the quadriceps[23,62], and can be implied for the local MF from studies on disc and nerve root trauma[66]. With joint distention from inflammation, the presence of AMI is distinguished by peripheral sensitization and resultant nociceptive signaling. Prolonged local tissue and joint sensitivity changes occur as a result of a reduced activation threshold in the articular free nerve endings supplied by Group III and IV joint afferents[67]. Consequently, normal non-noxious mechanical movement and activity causes articular structure stimulation which results in notable Group III and IV afferent discharge[67]. The release of inflammatory mediators increases this joint afferent discharge by sensitizing the free nerve endings innervated by Group III and

IV afferents. This is independent of nociceptive signals, as reducing pain does not necessarily reduce AMI's severity[21,62]. This action and the resultant reflex inhibition indicative of AMI, is also demonstrated for the lumbar MF at adjacent joints as well as the specific neural innovation levels, and in the presence of disc prolapse[66]. Both distention scenarios support the historical and recent recognition that AMI can occur regardless of the presence of structural damage[23,58,61,62] or inflammation[19,68,69].

Spinal pathways implicated in AMI: The spinal pathways are particularly associated with abnormal afferent discharge from the affected joint/s that can alter the excitability of the reflex pathways within the cord. This particularly affects the Group Ib inhibitory pathway and the associated Group Ia, II, III, and IV, the flexion reflex, and the gamma (γ)-loop[21]. However the neural connectivity at this level is able to show local neuroplastic change. A marker of observable neural change at the spinal level, the Hoffmann reflex (H-reflex), is measurable at the soleus through amplitude variations[70]. The H-reflex can be used to compare training effects in relation to the learning of a new skilled task, such as slacklining, with measures pre-activity (baseline), immediate post-activity (acquisition), and 24 h post-activity (retention). After 'acquisition' of a new skilled task, changes at the spinal level are general, but by 24 h these become task-specific. Consequently neural reorganization and generalization of spinal adaptations appears to be time dependent with the task specific adaption occurring after one day[71].

The Group Ib non-reciprocal inhibitory pathway utilizes signal relay actions to integrate sensory-motor information. Afferent musculo-tendinous junction neuronal signals are supplemented by Group Ia sensory fibers from the muscle-spindle stretch receptor, joint and peripheral sensory receptors through Group II, and unmyelinated/ thinly myelinated Group III and IV fibers[72]. In turn motor-efferent neuron actions are influenced. Consequently, these dual capacities influence the Ib fibers signaling where effusion increases Group II output, which increases AMI through facilitated muscle motoneuron pool inhibition[21,72].

The flexion reflex in contrast is a polysynaptic pathway with facilitated agonist excitability and concurrent reciprocal extensor inhibition that may cause AMI[68]. The distinction of the γ-loop spinal reflex circuit is that it enables automatic muscle tension regulation that ensures full activation during voluntary muscle contractions[21,73]. Consequently, γ-loop dysfunction will contribute to AMI[21] as joint injury reduces excitatory afferent output to the muscle γ-motoneuron pool which reduces discharge. This results in enhanced presynaptic inhibition of the muscle α-motoneuron pool *via* Ia afferent fibers[74]. The spinal inhibitory interneurons projecting into the Ia afferent fibers synaptic terminals adjust the neurotransmitter release levels in response to the afferent input, which, subsequently, modulates the synaptic efficacy[74].

Supra-spinal/ Central pathways implicated in AMI: These pathways are hypothesized as supra-spinal projections from the joint afferents that influence AMI[21,75]. The changes include four main areas: (1) Cortico-spinal excitability/activity affecting the somatosensory cortex[22]; (2) Brainstem descending pathways[76] and the flexion reflex[75], with efferent commands modulated by afferent input; (3) Individual voluntary effort[21]; and (4) 'Informed awareness' that amalgamates behavior and 'flow-experience'[77]. These supra-spinal actions affect both neuroplasticity[42,43,78] and movement-fluency[79] to facilitate global equilibrium control. Consequently, centrally mediated sources override existing down regulatory inhibition, through concurrent control of active spinal reflexes. This enables muscular re-activation that is repressed by central inhibition in response to negative afferent input from traumatized and/or distended joints.

AMI knowledge: Based on peripheral findings, particularly at the knee

Despite AMI's specific mechanism remaining unclear and the majority of knowledge being derived from recognized attributes post-trauma about the knee[22,62], ongoing research into AMI's physiological neuro-motor basis continues[5,6,17,22,23,63]. It is already well accepted that, in acute knee trauma maximizing available quadriceps activation through isometric exercises in the lowest IAP range is effective[80], however this is not always recognized as occurring when addressing AMI[23,68]. Consequently the focus in new research is on the CNS, particularly modification of the connectivity within the sensory-motor network[63]. This includes efferent corticospinal excitability alterations post joint injury that facilitate local muscle inhibition at the knee[81], and investigations in ACL injury related to therapeutic effectiveness in reducing AMI[22]. The verification of the consensus assumption that central brain origin output and inhibition is the primary explanation for quadriceps AMI[22,23,63], is demonstrated by brain motor area activation variations, found under MRI, between individuals with and without quadriceps AMI[69]. As these understandings improve, become recognized and accepted, the ability to progress and extrapolate such findings to the spine and MF-AMI depleted stabilisation will increase; as will the potential for management of NSLBP though AMI directed intervention to similarly evolve[5,6,17].

AMI knowledge: NSLBP implications and hypothesis evolved from the peripheral context

Using the knowledge and precedent understanding of AMI at the peripheral joints, particularly the knee[22,23,68], along with recent work from MF NMES[5,6,16], and understanding MF MCLs[17,51], the underlying basis of spinal MF-AMI can not only be implied but also understood through quantitative research.

This is supported by examples within the CNS neurophysiology, detailed above. This includes the analogous comparison of MF and quadriceps in the polysynaptic pathway of the flexion reflex with agonist flexion reflex excitability and concurrent reciprocal extensor inhibition[68]. Also the neuroplastic change, as a response to neuro-motor sequencing and muscle re-activation, that advantageously facilitates innate spinal stabilization[42,78]. Similarly the altered efferent corticospinal excitability following both joint injury and local manual intervention associated with local spinal muscle inhibition[82] supports this premise.

It seems then a logical understanding to extrapolate the knowledge of peripheral AMI, particularly the knee, to the spine, as a recognized mechanism where central brain origin output and inhibition is a primary explanation. Consequently this would be, at least in part, an indicative explanation of the MF deficiency[6], and by consequence that interventions directed at MF-AMI would facilitate NSLBP management[5,17].

NSLBP: RECOGNIZED THERAPEUTIC INTERVENTIONS

Medical, general, non-surgical, and surgical interventions

Patients with LBP seek and are recommended in clinical practice guidelines to use symptom relief in a stepped approach stratified by duration[3,7,8,48]. This approach is initially simple and non-interventional with moderate-quality evidence for advice, reassurance, and self-management. If improvement is insufficient, then more complex interventional techniques are considered including heat, massage, spinal manipulation, and acupuncture in the acute-subacute phase, which have low-quality evidence[3,7,48]. Progression to medications, such as non-steroidal anti-inflammatory drugs (NSAIDs), but not Paracetamol or muscle relaxants, has moderate-quality evidence, being initiated only if non-pharmacological therapies are unsuccessful. This is advised to be under medical guidance and with caution, particularly if further medication progression is made to antidepressants, opioids, or for any prolonged medication use, which have moderate-quality evidence, and anticonvulsants or other (new) drugs, which have insufficient-quality evidence[7,48,83]. At week 12, persistent pain is recognized and the recommended progression is stratified using a biopsychosocial (BPS) approach that employs patient reported questionnaires that screen for the risk of persistent problems and pain[3,7,84,85]: where low risk indicates simpler less intense support with continued therapy and group exercises[7]; while higher risk[84] indicates structured exercise regimes[86], psychological therapies including cognitive behavioral therapy[82], and a multimodal[7,85] and multidisciplinary approach, though the 'dosage' of input has no quality of evidence for a determined recommendation[3,7,47,48]. With suspicion of radiculopathy or specific pathology, or non-improvement following four weeks of additional therapy, a specialist referral is recommended[83].

This overall approach has gained consensus to achieve best practice[8] in NSLBP and reflects general musculoskeletal problems. The approach is supported by recent systematic reviews with 11 'musculoskeletal pain care' summarized recommendations[87] that parallel the stated NSLBP management[6,7,85]. However, only three recommendations were specific to interventions, (education/information, physical activity/exercise, and adjuvant manual therapy treatment), but they were supplemented with a BPS approach (activity through work)[87].

Other non-invasive, non-pharmacological interventions have mixed evidence in their effect. There is no evidence for therapeutic traction, heat, and US[5,48]; insufficient[48] or limited evidence for massage, non-structured exercise[86], and transcutaneous electrical nerve stimulation (TENS)[6]; and low to moderate evidence for photo-biomodulation (or laser therapy) and information/education alone[48]; but information/education improves significantly when combined with other therapies, particularly manual therapies[16,48] and therapeutic exercise[82], of which slacklining would be an example.

Invasive interventions have similar mixed findings in the evidence of their effect. These include: radiofrequency neurotomy, facet and nerve blocks, which have similarly varied findings with most recent meta-analyses questioning their use[88]. Similarly spinal cord stimulation (SCS) is questioned, though high frequency multi-column-SCS added to optimal medical management has higher evidence for gained effects, particularly individuals with multi-level non-specific changes and central sensitization[89]. Consequently, there remains a patient subgroup with significant symptoms and/or disability that fail with conventional management therapies and potentially require additional medical and invasive interventions[6].

AMI specific interventions for NSLBP

Several therapeutic interventions are demonstrated as effective in countering the presence of MF-AMI, though evidence is predominantly derived from effectiveness determined in musculoskeletal settings, particularly the lower limb and the quadriceps post knee trauma[23]. These techniques are generally achieved through a focus on local processes within two broad categories: (1) Modulation of joint afferent discharge; or (2) Muscle stimulation[20,22] as detailed below (in Supplementary material, Appendix 3), and summarized in Table 1. Consideration of management strategies for the lumbar MF-AMI that parallel those used for other AMI affected muscles, particularly quadriceps AMI at the knee, has occurred only recently through: involuntary-direct therapy *via* surgically introduced NEMS interventions[5,16]; while conservative approaches look to explain and utilize existing voluntary-direct and voluntary-indirect MCE therapy[6], and potentially involuntary-indirect therapeutic approaches, such as slacklining[17].

Joint afferent modulation to reduce discharge: The joint afferent modulation techniques reduce the neural signaling such that the CNS receives a lower degree of neural information and, subsequently, lowers the muscles inhibitory levels. Some of these therapies appear transferable to other body regions, such as the lumbar MF, and include: very low evidence for US[60] and vibration; low evidence for TENS[6], disputed evidence for NEMS[5,16] with reported findings both negative and positive[5,16], and moderate to strong evidence for cryotherapy[90].

Muscle stimulation and activation: The muscle stimulation techniques are achieved through four combinations of direct/indirect activation through voluntary/involuntary mechanisms. These target the restoring of stability, predominantly through the MF segmental stabilizing action[6,54], either alone[12] or with other ‘core’ muscles as previously noted[14,15]. This includes open/closed/composite kinetic-chain resistance[91] with fatiguing of the antagonist. However, many peripherally directed interventions for AMI may not be transferable to MF-AMI due to the MF diffuse fibers network, depth, additional overlying muscles, and that MF-AMI is virtually impossible to voluntarily activate[6].

Consequently, there is no definitive consensus on which specific therapeutic intervention/s demonstrate the most effective management for NSLBP, including that due to MF-AMI[6,13,85]. Ongoing disputes remain in the systematic reviews, meta-analyses, and RCTs, with discrepancies in guidelines[7,8,48], even within the same author group[83]. However, one area of consensus is management goals and aims, with recognition that for all NSLBP, including AMI affected joints and regions[5,6], low cost, self-administered interventions, such as adjuvant therapeutic exercise with the potential to alleviate symptoms and disability, should be considered and investigated[22,68].

Using published and current AMI cerebral-based research on peripheral joints, particularly the knee and the lower limb kinetic chain generally, the known positive effects from dis-inhibitory therapies that alter motor excitability, as cited in mild to moderate definitive scoping and systematic reviews[22], can be used and extrapolated to provide relevant applications to NSLBP. This leaves slacklining as a unique rehabilitation exercise, in that it addresses the entire affected lower limb kinetic chain coupled with the lumbo-pelvic region as a single unit[31,92], with the potential to overcome the presence of MF-AMI. This potential rehabilitation relationship between slacklining and MF-AMI for NSLBP management is significant, as slacklining presents an indirect-involuntary exercise therapy to address MF activation through a centrally mediated neural mechanism.

Table 1 Interventions that counter the effects of arthrogenic muscle inhibition

Modulation of joint afferent discharge		
Joint aspiration; intra-articular corticosteroid injection; nonsteroidal anti-inflammatory drugs; local anesthetic; cryotherapy; transcutaneous electrical nerve stimulation-TENS; electro-acupuncture; altering fluid distribution/capsular compliance		
Muscle stimulation		
	Voluntary activation	**Involuntary activation**
Direct	Therapeutic exercise; motor control exercise therapies: (1) Biofeedback/ultrasound guided; and (2) Individualized tailored hybrid convergence and divergence exercise-based approach of specific treatment of problems of the spine including: 'movement system impairment'; 'mechanical diagnosis and therapy' (MDT); 'integrated systems model' incorporates 'regional interdependence model'	(1) Neuromuscular electrical stimulation: (a) surgically implanted-effective; and (b) transcutaneous-ineffective; (2) Transcranial magnetic stimulation; and (3) Peripheral magnetic stimulation
Indirect	Therapeutic exercise: (1) Global/non-specific 'core stabilization exercise'; and (2) Specific 'core stabilization exercises' including: 'modern mind body' incorporating: Yoga, Tai Chi, Qigong, Pilates, Alexander, Feldenkrais, Bounce-Back, Calisthenics, Gyrokinesis, Gaga, Core-Align and Human Harmony; and MDT	Slacklining—possibly, *via* reducing down regulatory inhibition

TENS: Transcutaneous electrical nerve stimulation.

SLACKLINING AND ADJUVANT THERAPEUTIC EXERCISE

What is slacklining

A complete understanding of the full neuro-motor mechanism of slacklining remains incomplete, though several hypothetical models are proposed[28,92-95]. Most recently these models have been updated in an in-depth review with a revised paradigm proposed[31]. The summary slacklining definition presented in this paper's introduction can be expanded to include: Neuromechanical balance retention on a tightened webbing-band, fixed at each end, moveable in three dimensions during achievement of functional independence and dynamic stability from the interactions of the individual, where whole-body internal dynamics drive innate and learned responses to external environmental changes, that require adopting strategies that seek a compromise between maximum stability and minimal energy expenditure[26,28,31].

Consequently as a complex task[28,92], the individual learns, adapts, and adopts techniques that are self-developed neural strategies in response to the challenged balance and equilibrium[30], and can be quantified using self-organizing maps, a class of vector learning algorithms with the capacity to explain visualization techniques, topological retention and high-dimensional data-sets[94,96]. This results in lower-limb and core muscle activation as a primordial response[97,98] for balance retention to ensure postural stability[25,31] as a critical physical function[99]. This is achieved through a combination of: neurological system controls from centrally derived dampening of the down-regulation that causes reflex inhibition at both the central[78,100] and spinal segmental level[71]; and learned motor skills, from muscle recruitment through higher demand[78,101], that, subsequently improves coordination of movement and control[11,31]. However, there is also the consideration of mindfulness and flow-experience[77], the mind-body interaction that enables the movement-fluency[79] required to achieve and pursue slacklining as a tool for social, pleasure, pre- or re-habilitation purposes[29,37].

Efficacy of slacklining on AMI in NSLBP therapy

Slacklining has shown therapeutic promise in the clinical setting, particularly for the quadriceps AMI-inhibited post-trauma knee[25,26,30]. Slacklining may induce over twice the activation of four standardized quadriceps exercises with less than half the effort[30]. In employing this hypothesized basis, as previously detailed (presynaptic inhibitory actions on the CNS to over-ride central down-regulation induced muscle insufficiency[31,78,100]), for AMI-MF NSLBP case studies[17], the same neurophysiological, therapeutic-based reasoning of slacklining's action applies to the lumbo-pelvic musculature. The AMI-MF is targeted, in unison with other core stabilizing muscles[31], through an indirect-involuntary activation as a part of a whole body therapeutic exercise approach[79]. Though the therapeutic practice and research is still in its infancy and definitive evidence are lacking, the concept appears viable[17].

The consideration and inclusion of slacklining with other prevention and rehabilitation themes into NSLBP management derives from the sensory system's contributing triad of, proprioception, vision, and vestibular somatosensory inputs[102]. This is a consequence of slacklining's unique properties[30,31]: being a composite-chain activity, *i.e.*, there is a weak link in the kinetic chain resulting in abnormal motor synergy patterns due to the contact surface of the loaded limb/s having free, partially supported, but unstable three-dimensional movement on a recoil resistance surface[31,91]; and actions being distinctly different from other conventional balance activities[27] and apparatus[25,33]. The synergy of these qualities coupled with CNS contributions results in four integrated qualities[30,31]: balance—equilibrium control of dynamic movement and center-of-mass within the base of support[25]; postural control—positional control in space[25]; muscle strength- muscular generated forces[33]; and neuromechanical demand—integration of neurobiology and biomechanics[28].

Evidence of the efficacy of slacklining in therapy and rehabilitation

The therapeutic direction of slacklining has progressively evolved. In particular the past decade has shown increased recognition of its adjuvant role in both the prevention and management of injury. In prehabilitation this is demonstrated in falls prevention in the elderly[26], and specific sports including judo[103], basketball[33], badminton[104], handball[105], and football/soccer[106]. In rehabilitation this is demonstrated in orthopedics[17,30], neurology[31,34,107] including systematic review support for reduction of falls and freezing of gait for Parkinson's disease[36], sports training[95], general physical training[106], physical performance[33,103], and recreation[37].

For all forms of LBP the current recommendations for therapeutic exercise interventions suggest an individually tailored hybrid approach[108] that accounts for individual preferences and abilities, and considers aligning areas of convergence and divergence that incorporate MCE[14]. These approaches utilize a 'specific treatment of problems of the spine' (STOPS) approach[109], where the key application principles are derived from four diverse areas. These are established evidence based/informed clinical physical therapy approaches where motor control is either a central or adjuvant feature[14,108]: the kinesiopathologic mechanical LBP model of 'movement system impairment'[110]; McKenzie's model of 'mechanical diagnosis and therapy'[111]; individually tailored MCE for areas with assessed suboptimal features[12]; and the 'integrated systems model'[14] which is compatible with the musculoskeletal 'regional interdependence model'[14]. This STOPS approach serves to guide clinicians and provide the platform for the proposed hybrid model[14,108]. Consequently, slacklining can be seen to fit comfortably within a hybrid model[14,108] as part of the STOPS approach[109].

The inter-related effects of slacklining and AMI on NSLBP

To understand the hypothesized paradigm for how slacklining can address MF-AMI related NSLBP from the neuro-physiological perspective, it is critical to understand that AMI's defined CNS actions are present at each of the three levels[21,23] as discussed previously. The presence of AMI, as a centrally derived presynaptic inhibitory action[18,19,23], modifies existing down-regulation control with consequential local MF-AMI deficiency[78,100]. This paradigm is particularly significant for exercise based NSLBP rehabilitation therapies that aim to facilitate normal neuro-motor sequencing[93,94] for neuromuscular and proprioceptive impairments[11,31,79], as similarly targeted in other musculoskeletal problems with cortical excitability deficits that alter function. Slacklining's action as an adjuvant therapy within rehabilitation simultaneously addresses this neural compromise by providing an override of central inhibition that enables indirect activation of the local neuro-motor inhibited muscles, where the presence of the lowest available IAP joint range inhibition initiates AMI through central mediated processes. This occurs immediately and directly at all CNS levels with significant implications for the MF-AMI related NSLBP, and the use of therapeutic slacklining. This therapeutic slacklining can be achieved with minimal required learning or therapist input[30] to induce normalized function[11,79] of the descending inhibition alterations[21,31,59] and facilitate neuroplastic change[41,94]. Consequently, in the presence of AMI there is "… the need to address cortical function early in rehabilitation ..."[62].

This leaves an open and potential role for slacklining to be considered within 2-4 wk of any LBP rehabilitation initiation; but particularly NSLBP, when natural response progression falters, not simply as an alternative therapy and option of potential last resort. This therapeutic use could prevent the descent into persistent pain[5,6], particularly in circumstances such as soft tissue trauma and operative interventions, where AMI is likely to ensue[21,62]. The proposed model and paradigm shift on potential muscle specific activation, that this paper presents, can assist in closing what appears to be a 'knowledge gap', but may simply be a matter of interpretation, and consequently an 'implementation gap'[112].

A practical implementation of therapeutic slacklining exercises can be derived from the operational definition of 20-steps over 5-stages provided in previous publications[30]. These progressive stages enable the patient and clinician to both document and sequentially progress the slackline exercise capacity as an adjuvant to other incorporated and multi-modal and multi-practitioner approaches in a manner that is both self-taught and self-progressed. The sequence of steps and stages act as a guide and can be followed or altered for the individual (Table 2).

SLACKLINING'S NEURO-PHYSIOLOGICAL ACTIONS THAT POTENTIALLY COUNTER MF AMI INDUCED NON-SPECIFIC LBP

As presented above and per the aims, to rationalize why and how slacklining should be effective in reducing NSLBP symptoms, the ameliorating capacity is a consequence of slacklining's neuro-motor action that addresses the basis of MF-AMI[6,18-21,59], facilitating a reduction in down-regulated inhibition[31,78,100]. Consequently, this reductive capacity causes signal redundancy in the cerebral pre-synaptic inhibition section of the neuro-motor closed loop feedback system[102]. The action/s enable/s the brain to recourse to the normal or primordial signaling action[97,98,113] of neural flow through the spinal cord to the peripheral nerves and the local musculature, subsequently reducing the effect of AMI. This mechanism is supported by studies suggesting that central sensitization is influenced by impaired descending inhibition signaling[41]. This causes alterations in the individual's conditioned pain modulation (CPM) which is found in NSLBP patients. This slacklining action is hypothesized to occur through one or several of the four established neuro-physiological pathways detailed below[41,114].

Finite neural delay

The finite neural delay system occurs within the brain's limits for 'time available processing'[113,115]. To facilitate optimal use of available processing time during complex integrated neuro-motor control, such as that present with slacklining, the CNS combines and integrates: incoming/efferent signals through 'sensory weights', to ensure the required representation of all comparative contributions of each sensory system; and simplifies subsequent motor control through 'muscle synergies', where groups of muscles are combined as a common neural signal to control a range of movements, which simplifies motor-control[102,116]. Further, these neuromuscular strategies can be adapted and modulated by the individual to the required capacity necessary to facilitate stability[116]. However, despite these efficiency strategies, a significant neural load remains[117]. Consequently, the total information is interpreted as a 'package'[102], and as such requires processing time that exceeds the available finite neural delay; this consequently allows an override of existing down regulatory inhibition. Slacklining, being one such complex neuro-motor action, could induce such sequence override[31].

This is further supported by the understanding that nervous system processing is a principle consideration in relation to neural delay. This is due to the variations in different tissue-specific neural conductive pathways[118] and subsequent delays that result in varied reaction times[119] under different stressful situations[120]. These systems detect changes in desired positional orientation and react in an integrated manner. This maintains functional balance-control through a closed-loop feedback system with varied constraints on the sensory integration process, including that of the 'sensory weighting' discussed above[102,116]. Consequently, changes in motor activity or movement occur after nervous system processing[121], and are predominantly primordially protective responses designated to prevent injury[97,98,113].

NSLBP movement-control phenotypes, exercise reasoning hypothesis

The presence of two trunk movement control phenotypes[54] has been proposed as a model to facilitate the understanding of the inter-relation within trunk motor control between muscle activity and kinematics in LBP individuals[122]. In such a model there is a proposed spectrum continuity anchored at each end by control that is 'tight' and 'loose'. This may also be influenced by CPM response strategies that have a bias toward a pro-nociceptive phenotype in individuals presenting with NSLBP. Both the 'tight' and 'loose' control models are proposed to have beneficial effects, where 'tight' control protects against large tissue strains from uncontrolled movement, whereas 'loose' control protects against high muscle forces and resultant spinal compression[54]. This concept is consistent with Panjabi[9]'s modified model of spine stability that was

Table 2 Slacklining progressive competency phases—5 stages and 20 steps[30]

Stage and steps	Description of position
1 – Beginner: Stand	Each description of stages 1-4 is for the slackliner standing on a slackline of 3 m length at strong tension anchored at each end 25 cm above soft terrain such as sand or grass
1	Single leg stand – on the dominant leg
2	Single leg stand – on the non-dominant leg
3	Single leg stand – on dominant leg, other foot touching the side of the line 1 foot length in front of the weight-bearing foot
4	Single leg stand – on dominant leg, other foot touching the side of the line 1 foot length behind of the weight-bearing foot
5	Single leg on non-dominant leg, other foot touching the side of the line 1 foot length in front the weight-bearing foot
6	Single leg on non-dominant leg, other foot touching the side of the line 1 foot length behind of the weight-bearing foot
2 – Moderate: Walk	
1	Walk forward along the line with minimal to no pause between steps
2	Walk backward along the line with minimal to no pause between steps
3	Tandem stance with the dominant leg back or closest to the anchor point
4	Tandem stance with the dominant leg forward or furthest from the anchor point
3 – Intermediate: Tandem	
1	Tandem stance with the dominant leg behind, then turn or pivot 180° on both feet to the natural side so that the dominant then becomes forward
2	Tandem stance with the dominant leg forward then turn or pivot on both feet to the non-natural side so that the dominant leg is behind
3	Tandem stance with the dominant leg behind, then turn or pivot 180° on the dominant foot to the non-natural side so that the non-dominant foot crosses over and returns to the forward position
4	Tandem stance with the dominant leg in front, then turn or pivot 180° on the non-dominant foot to the non-natural side so that the dominant foot crosses over and returns to the forward position
5	Side stand 'surf posture' – feet perpendicular to slackline and balance
4 – Advanced: Squats	
1	'Surfer' position and squat down feet perpendicular to the line approaching buttocks to the line
2	Squat in tandem, dominant leg behind – feet along the line approaching buttocks to the line
3	Squat in tandem dominant leg in front – feet along the line approaching buttocks to the line
4	Single leg squat all weight on the dominant leg – approaching buttocks to the line
5	Single leg squat all weight on the non-dominant leg – approaching buttocks to the line
5 – Extreme	Without using arms, without sight, bouncing
Other – tricks: Performance	Heel raises, walking on toes, jumps, spins, somersaults on line or as dismounts
	External focus (*e.g.*, throwing ball, juggling ball)
	Surfing (on very slack line) with oscillations or swinging perpendicular to the line

Slackline length and tension can be changed to modify the difficulty level.

evolved to include motor control[11]. Should these proposed differential movement control phenotypes exist, then interventions using different motor-control exercises would be required, or a single exercise that provides the ability to address both forms[54,122], particularly if they truly are parts of the same spectrum[14]. Slacklining as a unique complex neuromechanical action could potentially be such an exercise with this dual capacity[30,31].

The inhibition of action and the innate primordial imperative

A primary brain function is behavioral organization to determine 'action' or 'inhibition of action'[98]. This involves activation of the behavioral inhibition system (BIS)[97], which occurs in the presence of threats and endangered health, to enable choice of the least detrimental option, *e.g.*, injury is preferred to death. It also, additionally, occurs in three circumstances when: no previous response pattern exists; danger cannot be predicted; or the instinctive fight/flight/freeze response (FFFR) is impossible[97]. The FFFR is instigated by fear and relates to individual underlying differences and experiences that, consequently, affect the level of adrenaline production. All three additional BIS circumstances would essentially be present in an initial exposure to slacklining[30,31]. Consequently, this BIS activation pathway may explain the pre-synaptic AMI override, but such an assumption must be taken within the context of reinforcement sensitivity theory (RST). This RST predicts that the BIS role in coping-motivated problem solving through its central role in anxiety is moderated by the behavioral approach system[97]. Further, it is important to recognize that BIS activation causes neuroendocrine responses; these involve multi-adrenocorticotropic hormone production by the hypothalamus, pituitary and adrenal axis, as part of the stress response. This in turn leads to glucocorticoid secretion and elevated cortisol levels, which if prolonged or chronically elevated have detrimental consequences including reductions in hippocampal volume which, subsequently, effect spatial and hippocampal-dependent learning and memory task capacity[15].

Preservation of existence is every organism's primordial imperative[97] as the brain's purpose is to ensure survival, through this aforementioned action, or inhibition of action[97]; not simply to think, but to act. This is because humans exist to maintain the structures that sustain life[98] and to reproduce for the optimal potential of natural selection through self-organization. The nervous system, consequently, enables species to act both within and upon their environment with the intended purpose of survival[99]. As such, the actions of slacklining through pre-synaptic inhibition could result from the consequential role of the inhibition of action and the innate primordial imperative[97,98].

Accentuated corticospinal drive

Positive influence on corticospinal excitability occurs in the presence of individual muscular feedback and joint pathology[68]. These cause an accentuated modulation in the CNS corticospinal drive[21]. The consequential effect is an override of pre-synaptic inhibition that enables a counteraction to the α-motoneuron inhibition by the spinal reflex pathways[23]. This positive influence on local AMI influenced muscles[69], particularly as demonstrated in the knee[22,23,30,31], could account for the capacity to initiate MF activation through the various direct and indirect, voluntary and involuntary mechanisms previously discussed.

CONCLUSION

Slacklining is a strategic indirect-involuntary therapeutic exercise that can facilitate the activation of MF-AMI deficient muscles; however, a thorough understanding of its neuro-motor mechanism of action remains incomplete. Slacklining has demonstrated clinical effects that overcome AMI in peripheral joints and recent case-studies indicate slacklining's potential in reducing MF-AMI related NSLBP. Slacklining's actions of effect are proposed to be provided by an: over-ride and inhibition of CNS down-regulatory induced MF-AMI, which normalizes the MF neuro-motor sequencing and muscle re-activation. These actions in-turn suggest slacklining as a potential adjuvant therapy that may address and reduce NSLBP symptoms and disability. Slacklining is simple to administer, use, and progress. Existing slacklining research on the neurological basis of effect, particularly in relation to AMI, has adequate acceptance to facilitate its introduction into NSLBP rehabilitation. However, what appears as a 'knowledge gap' could simply be interpretive, and merely an 'implementation gap' where the rehabilitation clinicians prescribing protocols are yet to recognize the full potential of this ancient excise and take it back to the future. Further investigation is required in research, cohort, and clinical populations to determine slacklining's efficacy, dose-response, and optimal time of implementation during pre- re-habilitation in managing MF-AMI deficient NSLBP.

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MINIREVIEWS

Lateral unicompartmental knee arthroplasty: A review

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Abstract

Isolated lateral compartment osteoarthritis of the knee is a rare condition affecting approximately 1% of the population, which is ten times less common than osteoarthritis affecting only the medial compartment. Unicompartmental knee arthroplasty (UKA) has many potential advantages over total knee arthroplasty. The benefits of UKA include a smaller incision, preservation of more native tissue (including cruciate ligaments and bone), decreased blood loss, and better overall proprioception. When UKA was first introduced in the 1970s, the outcomes of medial UKA (MUKA) were poor, but the few cases of lateral UKA (LUKA) showed promise. Since that time, there has been a relative paucity of literature focused specifically on LUKA given it is a rare procedure. Refinements in patient selection criteria, implant design, and surgical technique have been made leading to increased popularity. A review of the recent literature reveals that LUKA is associated with excellent long-term clinical outcomes and implant survivorship when performed in properly selected patients. Implant design options include fixed *vs* mobile bearing as well as metal backed *vs* all polyethylene tibial component, with improved outcomes noted with fixed bearing designs. Three reasons cited for revision (*i.e.*, fracture of the femoral component, fracture of the tibial component, and valgus malalignment) had been reported in past literature but not recently. Presently, while rare, the most common cause of failure and need for revision are osteoarthritis progression and aseptic loosening. Despite the need for an occasional revision procedure, the survivorship of LUKA is comparable to MUKA, although it should be noted that outcomes of MUKA have been notably varied. Continued pursuit of improved techniques and implant designs will continue to show LUKA to be an excellent procedure for appropriately indicated

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Core Tip: Lateral unicompartmental knee arthroplasty (LUKA) is an uncommon procedure, that when indicated appropriately, shows promising results for patients with isolated lateral compartment osteoarthritis. Recent literature has shown good long-term outcomes for LUKA. Continued pursuit of improved techniques and implant designs will continue to show LUKA to be an excellent procedure for appropriately indicated patients. This paper reviews patient selection, surgical techniques, and outcomes for LUKA.

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INTRODUCTION

Isolated lateral compartment osteoarthritis of the knee is a rare condition affecting approximately 1% of the population, which is ten times less common than osteoarthritis affecting only the medial compartment[1]. The clinical outcome of unicompartmental knee arthroplasty (UKA) has been a topic of renewed interest in the orthopaedic literature. Initial studies indicated poor outcomes following UKA; however, patient selection, surgical technique, and implant design changes have changed over the years[2-6]. This has led to many potential advantages over its total knee arthroplasty (TKA) counterpart. Performing a UKA allows for a smaller incision, less bone and soft tissue resection, less blood loss, and improved proprioception[7-11]. In addition, patients show decreased rates of post-operative infection and thromboembolic disease, decreased pain, and improved range of motion[9,11]. Furthermore, improvements have been seen in the form of shorter hospital stays as well as quicker rehabilitation[9,12,13]. Registry studies have indicated higher revision rates after primary UKA when compared with TKA. In contrast to the registry data, multiple studies have shown UKA implant survivorship to be comparable TKA[9,12,14,15]. Other studies have also indicated improved patient satisfaction likely a result of perceived normal knee function[16,17]. Biomechanical studies have confirmed that tibial axial rotation and femoral rollback following UKA more closely recapitulate normal knee kinematics than that following TKA[18].

Even though multiple studies have documented the success of lateral UKA (LUKA), it is not commonly performed. In fact, medial UKAs (MUKAs) are performed ten times more often than LUKAs. Overall, LUKA accounts for less than 1% all of knee arthroplasty procedures[19].

The small number of LUKAs performed since the development of the procedure many years ago is surprising. The original reports from that era implied that MUKA was not a great long-term option for treatment of unicompartmental osteoarthritis, while LUKA appeared to be much more promising[3-6]. Following refinements in patient selection criteria, surgical technique, and implant design, improved results for both medial and LUKA were seen in the 1980s[2]. Improved survivorship was noted at ten years and reported to be only slightly less than that seen for TKA at the time[20-22]. Studies on long-term outcomes following LUKA are hard to come by. However, more recent studies on LUKA show 100% survivorship at mid-term and long-term follow up[23,24]. These reports suggest that outcomes of LUKA are at least comparable to, if not superior to, those of MUKA. Recently, a meta-analysis of survival between medial and LUKAs showed no difference in short, mid-term, and long-term survival. In addition, there was no difference in pain relief or functional improvement between the two procedures[25].

BIOMECHANICS OF THE LATERAL KNEE

The lateral compartment of the knee is significantly different than the medial compartment in regard to the anatomy and biomechanics. Implants and surgical techniques must be specific to the lateral compartment, thus accounting for its unique characteristics.

Anatomic differences between the medial and lateral compartments include differences in posterior tibial slopes and anteroposterior (AP) dimensions in tibial plateaus[26,27]. In addition, the lateral plateau is convex and sits slightly more proximal than the medial plateau. Furthermore, the C-shaped lateral meniscus is more mobile allowing for more movement within the lateral compartment compared with the medial during normal knee kinematics. In normal knees, the femur rotates externally with flexion when the foot is left in neutral. At 40° of flexion, the flexion facet centers of the femur displace 4-5 mm in the AP plane such that there is anterior translation on the medial femoral condyle and posterior translation of the lateral femoral condyle[28]. Furthermore, the degree of femoral rollback is greater in the lateral knee than the medial knee[29].

As a result of these differences in anatomy and biomechanics, contact stresses develop in different regions as arthritis develops in the medial and lateral compartments. Weidow *et al*[29] localized regions of cartilage wear for cases of medial and lateral compartment arthritis. In medial osteoarthritis, tibial cartilage wear is located anteriorly, while in lateral osteoarthritis, wear is greater in central and posterior regions.

INDICATIONS

Over the years, different criteria have been included to pin point the perfect candidate for LUKA in order to improve outcomes. Most authors tend to refer to similar parameters, however they often disagree on specific cutoffs and values. Indications and contraindications proposed by Scott[19] are listed in Table 1.

Isolated lateral compartment osteoarthritis with axial deviation less than 10°-20° from neutral mechanical axis is a primary indication for LUKA. Radiographic evaluation should confirm the absence of advanced osteoarthritis in the medial and patellofemoral compartments. If joint space is preserved in the medial compartment, chondrocalcinosis or osteophytes are not an absolute contraindication. Provided the patient is not symptomatic for patellofemoral symptoms, radiographic evidence of patellofemoral osteoarthritis is also in itself not a contraindication. Burger *et al*[30] demonstrated that mild to moderate preoperative radiological degenerative changes and malalignment of the patellofemoral joint are not associated with poor patient reported outcomes at midterm follow up after lateral fixed bearing UKA.

Other commonly reported prerequisites are pre-operative range of knee flexion greater than 90°-100°, full knee extension, and tibiofemoral angles between physiological valgus and 10° varus without subluxation[31]. Some of the other indications have been adopted from literature based on MUKA. Ideal patient characteristics include an intact anterior cruciate ligament (ACL), weight less than 82 kg, and absence of significant inflammatory synovitis[32]. A fixed flexion deformity greater than 10° that cannot be corrected by ligamentous release nor removal of osteophytes is also considered a relative contraindication[24,33], especially given that a UKA relies heavily on normal knee biomechanics in order to maintain function and stability. Motion and stability are based on balance between static and dynamic support around the knee. If the release of soft tissue and osteophytes does not correct the deformity, larger bone cuts would need to be made in order to gain full extension, thus altering the normal kinematics of the knee.

EXPANDING INDICATIONS

While well-established guidelines have improved overall outcomes, expansion of traditional criteria has been favorable with no obvious decline in quality. Age and body mass index of patients at time of surgery have been expanded. While there is not any specific study looking at survivorship based on age as their primary outcome, there are some studies that indicate age is not a factor in outcomes. Lustig *et al*[34] showed excellent pain relief, improved function, and survivorship of 100% at 5 years and 10 years in patients with an average age of 50 years old (range 25-67). In a

Table 1 Traditional indications and contraindications

Indications
Predominantly isolated lateral compartment osteoarthritis
Angular deformity < 10°
Body weight < 80 kg
Contraindications
Flexion contracture > 15°
ACL and/or MCL insufficiency
Inflammatory synovitis

ACL: Anterior cruciate ligament; MCL: Medial collateral ligament.

retrospective review that included 31 LUKA, Xing *et al*[35] showed that the outcome was not influenced by the patients age.

Body mass index continues to be a topic of discussion in regard to success of knee arthroplasty. Multiple authors have shown based on long-term survivorship of LUKA that obesity alone should not be a contraindication[16,33]. In a study that included a cohort of obese patients, Swienckowski and Pennington[23] showed LUKA survivorship to be 100% at 12.4 years. In addition, Xing *et al*[35], found no correlation with obesity and LUKA outcomes. In a study that included 55 patients that underwent LUKA, Cavaignac *et al*[36] showed that weight and body mass index did not influence the outcome or survival. In fact, their results trended in the direction that weight plays a part in reducing the risk of revision, although their results were not significant.

Traditionally, the lack of a functional ACL was a contraindication for LUKA. This is a result of greater translation between the tibia and femur in the lateral compartment when the ACL is deficient. Therefore, this leads to abnormal kinematics and increased contact stresses, thus creating a higher implant failure rate[37]. However, Volpi *et al*[38] proposes that ACL insufficiency in patients over 70 years of age is not a reason to avoid LUKA. In his study, he reported on 3 patients with deficient ACLs that underwent LUKA, and they had excellent Hospital for Special Surgery scores at mid-term follow-up (range 2-5 years). While this study does show promising results of a LUKA in an ACL deficient knee, 3 patients is not enough to offer strong conclusions regarding its efficacy, and has only been found in a specific patient population of patients over age 70. Future research may offer more insight into the benefits of LUKA in ACL deficient knees; however, no formal conclusions can be made at this time. As technology improves, implants are moving toward restoring more native kinematics of the knee, thus offering a more stable implant even in the setting of an ACL deficient knee.

In addition to osteoarthritis as a diagnostic indication, the presence of primary osteonecrosis and post-traumatic arthritis are also indications for LUKA. Multiple studies have indicated excellent long-term survivorship in the setting of osteonecrosis and post traumatic arthritis[16,33,34]. Secondary osteonecrosis and inflammatory arthritis have been reported as contraindications to LUKA due to the fact they are likely going to involve the other knee compartments leading to early failure[39].

PRE-OPERATIVE ASSESSMENT

The pre-operative evaluation of a patient should be focused and intent on elucidating key pieces of information in the patients' history that would help the physician indicate the patient for a LUKA. A detailed history and physical exam should focus on location of the pain, timing and length of symptoms, and previous knee injuries/surgeries. Pain localization to the lateral joint line is imperative and indicates lateral joint pathology. Pain that is general or localized to other parts of the knee should be examined closer, as the patient may have pathology in other compartments and would therefore not be indicated for a LUKA. According to Bert[40]'s "one finger test", the patient points with one finger to the lateral compartment of the knee. In addition, the patient should be questioned about knee stiffness, mechanical instability, progression of functional limitations, and daily functional demands. On physical exam, evaluation should consist of overall limb alignment with comparisons made with the opposite knee. Range of motion, gait analysis, and presence or absence of effusion should also be evaluated during the initial exam.

Four different radiographic views are recommended as part of the initial evaluation: weight-bearing anteroposterior, lateral, patellofemoral skyline, and a 45°-flexed knee tunnel view. In addition, stress radiographs can assist in making an accurate diagnosis and development of an appropriate preoperative plan. Gibson and Goodfellow[41] noted that if a stressed knee retains a width of 5 mm or more in the compressed compartment, the cartilage within that compartment is normal. Stress radiographs will also provide additional information on the reducibility of any deformity that may assist in determining if a LUKA is the correct procedure for the patient. Magnetic resonance imaging is typically not needed; however can be useful to further identify soft-tissue injuries.

Following a thorough examination and review of radiographic images, the decision to perform a LUKA *vs* perform a TKA should be determined prior to surgery, however being ready to convert to a TKA is imperative as plans may change after direct visual inspection of other compartments intra-operatively.

APPROACHES

Medial and lateral parapatellar approaches have been described for LUKA and offer good results. A lateral parapatellar approach provides direct visualization into the lateral compartment, thus allowing for a potentially smaller incision and less technically demanding than a medial approach. A main drawback on the lateral approach is that many orthopaedic surgeons are less familiar with this approach, which may lead to increased surgical time. In addition, there may be a concern for devascularization of the patella if a future medial parapatellar incision is needed. Despite all this, a lateral parapatellar approach has shown to be successful in LUKA. Swienckowski and Pennington[23] showed excellent long-term results using a lateral approach to the knee. In addition, Lustig *et al*[34] had a 100% survivorship at 10 years using a lateral parapatellar approach.

A medial parapatellar approach is another option for performing a LUKA. It is much more widely familiar to most orthopaedic surgeons and thus provides a level of comfort when performing the procedure. Sah and Scott[24] utilized a medial parapatellar approach and showed excellent outcomes at 5.2 years postoperatively. They showed that while a lateral parapatellar arthrotomy is more common to enter the lateral compartment, performing a LUKA through a medial approach provides a safe, effective, extensile and viable alternative.

When medial and lateral approaches were compared, Edmiston *et al*[42] showed improved postoperative flexion and greater improvement in flexion from preoperative measurements in the lateral approach group. Despite these findings, they also showed no difference between medial and lateral approaches in regard to revision rates or clinical outcome[42]. Both medial and lateral approaches offer excellent results. The approach used should be based on surgeon preference taking into consideration patient specific factors that may be present at the time of surgery.

OUTCOMES

Table 2[6,16,23,24,33,34,43-50] indicates the literature available for the survivorship of LUKA and the need for revision procedures. Of note, over the years there has been many different implant designs which is reflected in the literature laid out in Table 2. These studies include tibial components that are fixed *vs* mobile bearing as well as metal backed or all-polyethylene. Prior studies comparing these two tibial designs have focused on MUKAs with much more limited research on LUKA. Studies based on MUKAs show a superiority of metal back tibial designs over an all poly designs[51,52]. van der List *et al*[51] reported improved functional outcomes when using metal back implants and Koh *et al*[52] showed an increased failure rate within 2 years of all poly implants. While these studies show better results with metal backed implants, it is important to note these studied on MUKA and not LUKA. As discussed, the lateral compartment has different anatomy and biomechanics and therefore these benefits may or may not be seen in LUKA. There is very little literature comparing metal backed *vs* all poly tibial designs. Based on the few studies reported to date, no significant differences can be observed between metal backed or all-polyethylene tibial components[23,24,43]. However, it is

Table 2 Survivorship of lateral unicompartmental knee arthroplasty

Ref.	Number of UKA	Type of implant	Mean follow-up (yr)	Survivorship (number of revisions)
Scott and Santore[6] (1981)	12	Cemented, all poly tibia	3.5 (2-6)	83% at 3.5 yr (2)
Marmor[47] (1984)	14	Cemented, all poly tibia	7.4 (2.5-9.83)	NA (2)
Gunther *et al*[48] (1996)	53	Cemented, metal-backed, mobile-bearing	5 (2.5-9.83)	82% at 5 yr (11)
Ohdera *et al*[49] (2001)	18	Four different designs	8.25 (5-15.75)	NA (2)
Ashraf *et al*[33] (2002)	83	Cemented all poly tibia	9 (2-21)	74% at 15 yr (15)
O'Rourke *et al*[50] (2005)	14	Cemented all poly tibia	24 (17-28)	72% at 25 yr (2)
Swienckowski and Pennington[23] (2004)	29	Cemented, metal-backed (75%); all poly tibia (25%)	12.4 (3.1-15.6)	100% at 12.4 yr (0)
Sah and Scott[24] (2007)	49	Three different designs	5.2 (2-14)	100% at 5.4 yr (0)
Argenson *et al*[16] (2008)	38	Four different designs	12.6 (3-23)	84% at 16 yr (5)
Lustig *et al*[43] (2011)	54	Cemented, all poly tibia	8.4 (5-16)	98% at 10 yr (1)
Lustig *et al*[34] (2012)	13	Three different designs	10.2 (3-22.1)	100% at 5 yr; 80% at 15 yr (3)
Heyse *et al*[44] (2012)	50	Full poly, metal-backed cemented, metal-backed uncemented	10.8 (5-16)	91.8% at 10 and 15 yr
Fornell *et al*[45] (2018)	41	Cemented, metal-backed, mobile bearing design	4.1 (2-7)	97.5% at 5 yr
Zambianchi *et al*[46] (2020)	67	Fixed bearing metal backed design	3	100% at 3 yr (0)

UKA: Unicompartmental knee arthroplasty; NA: Not available.

reported that there is an increase in polyethylene dislocations associated with mobile bearing designs which has an effect on outcomes. When using a mobile bearing designed implant, Gunther *et al*[48] showed a 10% rate of inlay dislocations. This is likely due to greater translation of the lateral femoral condyle on the lateral tibial plateau during knee range of motion[18]. More recently, domed shaped mobile bearing implants were designed to imitate the native convexity of the lateral tibial plateau however more data is needed on this type of design to make a judgement on its effectiveness. A recent systematic review noted mobile bearing LUKAs had a higher rate of revision compared to fixed bearing designs with regard to short to mid-term survivorship, however clinical outcomes were similar[53]. At present, fixed bearing implant design is preferable given the survivorship and low failure rate.

Table 2 also shows three more recent publications that are important to highlight[23,24,34]. Swienckowski and Pennington[23] and Sah and Scott[24] showed 100% survivorship of LUKA at long-term (12.4 years) and mid-term intervals (5.2 years), respectively. Lustig *et al*[34] also had similar results and showed survivorship to be 100% at mid-term follow up and 80% at long-term follow-up after undergoing LUKA for post-traumatic arthritis secondary to lateral tibial plateau fractures. Heyse *et al*[44] showed a survivorship of LUKA to be 91.8% at 10 years and 15 years in patients less than 60 years old at the time of the index operation. They also found revision rates to be comparable to those in which UKA was performed in the elderly population. In addition, Fornell *et al*[45] showed 97.5% survival at 5 years. Overall survivorship of LUKA has improved since it was first attempted. Literature shows excellent survivorship at the 5- and 10-year time intervals with only minor drops at long term intervals.

More recently, the literature has investigated robot assisted LUKA to improve the quality of the procedure. Zambianchi *et al*[46] found 100% survival rate in 67 patients receiving LUKA when a robotic arm assisted procedure was performed. In a retrospective study comparing robotic assisted LUKA with a conventional technique, Canetti *et al*[54] showed that a robotic assisted surgical technique provide a quicker return to sports at an average of 4.2 mo *vs* 10.5 mo for the conventional technique (*i.e.*, hiking, cycling, swimming, skiing). While this was a small cohort of 28 patients who underwent LUKA, both groups were comparable preoperatively. Decisions about while whether to use robot assisted technique *vs* conventional were determined by robot availability as opposed to patient specific differences. The overall return to sports was high and comparable between both groups.

Argenson *et al*[16] reported a survivorship of 84% at 16 years after undergoing LUKA for osteoarthritis. While these results are disappointing, it is important to note that this retrospective review included cases from February 1982 and December 2004. As discussed above, there have been many changes to surgical technique, implant design, indications, and contraindications. In this study, 4/5 revision surgeries were completed prior to 1989, when patient selection criteria were not nearly as strict as it is today. In addition, previously surgical instrumentation was not as refined and therefore much of the procedure relied on handmade cuts for proper placement of the implants. Implant choice may have also contributed implant failure. Gunther *et al*[48] reported a 21% failure rate in the lateral compartment with a 10% rate of bearing dislocation with the use of a mobile-bearing Oxford unicompartmental prosthesis. While this is cause for concern, this high failure rate in mobile bearing componenets has not been reproduced in more recent studies[45].

FAILURE AND REVISION SURGERY

Following LUKA, revision surgery is occasionally needed. In a recent systematic review by Ernstbrunner, they cited the most common cause of failure in LUKA was osteoarthritis progression and aseptic loosening noted in 30% and 22% respectively. Other causes of failure included instability, unexplained pain, infection, polyethylene wear, and bearing dislocation. In addition, they noted that bearing dislocation was the most common cause of early failure and the most common cause of failure when mobile bearing implants were used. Late failures were most commonly caused by osteoarthritis progression[55]. In a different systematic review investigating both cohort and registry data, van der List *et al*[56] noted the most common modes of failure to be osteoarthritis (29%), aseptic loosening (23%), and bearing dislocation (10%). In an evaluation of a Dutch arthroplasty register Burger *et al*[57] found a 12.9% 5 year revision rate for LUKA, citing progression of osteoarthritis as the main reason for revision. In addition, in a cohort that included 32 patients, Walton reported progression of osteoarthritis in 18%-34% of LUKAs[58]. While some authors admit to progression of osteoarthritis to other compartments, they tend to believe it remains clinically asymptomatic and therefore revision is not needed[31]. Two studies highlighted the need for revision surgery due to progression of osteoarthritis. Ashraf *et al*[33] revised 9/15 LUKAs and Argenson *et al*[16] revised 4/5 for osteoarthritis progression to other compartments.

Other reasons for revision that have been cited are fracture of the femoral or tibial component and valgus malalignment. These complications have not been found in recent literature and are therefore likely the result of past poor patient selection, surgical technique, and implant design. For example, Ashraf *et al*[33] completed 4 revisions prior to 1988 for a fractured femoral component. Subsequent design alterations have made the femoral component stronger making this complication rare. Argenson *et al*[16] revised 1 implant for a tibial plateau fracture that was likely caused by a technical error at the time of surgery. Valgus malalignment was another common cause for poor results following LUKA during its early days of development. Cameron *et al*[59] reported difficulty correcting valgus malalignment as a cause for poor results in 9/20 LUKA. Improvements in patient selection have since been modified to include fixed valgus deformity as a contraindication due to previous poor results.

Despite increasing literature regarding revision surgery from a LUKA, it remains controversial. Ease of revision often favors performing a UKA[60]. In a study of 54 patients undergoing revision to TKA after a UKA (9 lateral, 45 medial), Châtain *et al*[60] found better results with revision from a UKA to a TKA *vs* patients who underwent a tibial valgus osteotomy. In turn they also found less satisfactory results when a UKA was converted to a TKA than a primary TKA initially[60]. Lewold *et al*[61] found that the risk of having a second revision was greater than 3 times higher for failed UKAs revised to a new UKA than for those that were originally revised to a TKA. The re-revision rate was reduced to 7% after converting the initial UKA to a TKA[61]. Robertsson and W-Dahl[62] indicated a significantly higher risk of revision after a TKA in patients that previously underwent a UKA or closed wedge HTO. While it has been well documented that TKA's are more reliable in terms of survivorship and less complications overall, there is still a lot of debate on whether undergoing a UKA is advised over a TKA at the index procedure. It should be noted that a revision of a UKA can often be done with primary TKA implant without then need for revision stems, whereas a revision of a primary TKA would require a more involved and invasive procedure. In many cases, a LUKA offers a great option for patients that meet the indications; however, they do need to be advised on the comparison between that and undergoing a TKA.

CONCLUSION

Although LUKA is sparingly utilized, the procedure does lead to excellent clinical outcomes and high long-term implant survivorship rates. The increase in survivorship and decrease in revision rates of LUKA can be attributed to better-defined patient selection criteria, improvements in surgical technique and instrumentation, and modifications of implant design to better accommodate the lateral compartment. Currently the literature supports improved outcomes when using fixed bearing designs. Given the paucity of literature on the topic, the superiority of metal backed *vs* all polyethylene tibial components has not been borne out despite the superiority of metal backed implants for MUKA. The breadth of research into LUKA has flourished within the last 10 years and will likely continue along that path as the procedure is becoming more frequent. LUKA now has similar survival rates and functional outcomes to MUKA within the literature. Continued pursuit of improved techniques and implant designs will continue to show LUKA to be an excellent procedure for appropriately indicated patients.

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MINIREVIEWS

Fracture of ossified Achilles tendons: A review of cases

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Abstract

Fracture of an ossification of the Achilles tendon (OAT) is a rare entity, and its etiology, pathology, and treatment remain unclear. We reviewed and scrutinized 18 cases (16 articles) of the fracture of an OAT. The most common etiologies of the ossifications include previous surgery and trauma. The fractures often occur without any trigger or with minimal trigger. The long, > 5 cm, ossification in the body of the Achilles tendon may have a higher risk of fracture. The OAT itself is often asymptomatic; however, its fracture causes severe local pain, swelling, and weakness of plantar flexion, which forces patients to undergo aggressive treatments. Regarding the treatments of the fractures, nonoperative treatment by immobilizing ankle joint could be an option for elderly patients. However, because it often cannot produce satisfactory results in younger patients, surgical treatment is typically recommended. Excision of the fractured mass and repairing the tendon is applicable if the remnant is enough. If there is a defect after the excision, reconstruction with autologous grafts or adjacent tendon transfer is performed. Gastrocnemius fascia turndown flap, hamstring tendon and tensor fascia lata are used as autologous grafts, whereas peroneus brevis and flexor hallucis longus tendons are used for the tendon transfer. If the fracture of an OAT is treated properly, the functional result will be satisfactory.

Key Words: Achilles tendon; Ossification; Fracture; Tissue grafting; Tendon transfer; Treatment

Core Tip: This review paper aims to provide an overview of the fracture of an

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ossification of the Achilles tendon. This fracture is distinct in that it occurs with minimal or no triggers. Nonoperative treatments may offer acceptable results for the elderly; however, surgeries should be recommended in younger patients. Following excision of the fractured mass, repairing the tendon is only applicable if the remnant is enough. If there is a defect after the excision, reconstruction with auto-grafts or adjacent tendon transfer is performed. Various kinds of tissues are used for the reconstruction. Treated properly, the functional result will be satisfactory.

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INTRODUCTION

Ossification of the Achilles tendon (OAT) is a rare entity. Among them, fracture of an OAT (FOAT) is exceptionally rare. Therefore, perspectives of the etiology, pathology, and the treatment of the FOAT have not yet been unified. This review aims to summarize and evaluate the current literature on the FOAT and describe current concept of etiology, pathology, and treatment of this condition.

LITERATURE SEARCH

Systematic searches of PubMed were performed in August 2020 to identify studies relating to FOAT. The outline of the search strategy is shown in Figure 1. First, we identified 54 relevant articles by using the specified terms shown in Figure 1. Second, we excluded the articles which were not written in English. Third, articles were screened based on their title and abstract. Fourth, articles were further screened based on the full text and those that described the FOAT cases were selected. Finally, we scrutinized the reference lists of the included 15 articles and added one proper article. As a result, we identified 16 articles. All of them were case reports and included cases of 18 fractures in 16 patients (two patients had the fracture on both sides[1,2]). We show the summary of all the 16 articles in Table 1.

ETIOLOGIES OF OAT

Past studies revealed that OAT occurred more frequently in men than in women[1,3,4]. Although the exact mechanism of ossification is unclear, the most commonly known etiologies are previous trauma and surgery[4]. In addition, infectious, metabolic, and systemic diseases such as syphilis, gastrocnemius abscess, osteomyelitis of the calcaneum, gout, diabetes, Wilson's disease, ochronosis, diffuse idiopathic skeletal hyperostosis, Reiter's syndrome, and ankylosing spondylitis may also cause ossification[3,5-9].

ETIOLOGIES OF FOAT

Only a small number of patients with OAT experience the FOAT. We show the summary of all the FOAT cases in Table 1. Etiologies of FOAT are similar to those of OAT. Among the 16 patients with the FOAT, 10 were men and 6 were women. Six patients had a history of previous surgery and 5 had a history of previous trauma. Among the 6 cases, who had experienced previous surgeries, the most common underlying cause was talipes equinovarus (5 cases)[1-3,5,10], followed by poliomyelitis (1 case)[11]. Achilles tendon rupture[12], ankle dislocation[9], distal tibial fracture[13], deep laceration of the calf[6] and soft tissue injury of the calf[14] were described as the details of the previous trauma.

Table 1 Summary of reported cases of the fracture of an ossification of the Achilles tendon

Ref.	Patient		Size	Cause of ossification			Onset of fracture	Treatment	Histology	Follow-up period	Result
	Age	Sex		Previous trauma	Previous surgery	Other factors					
Lotke[1] (1970)	61	F	NA	-	+	-	Standing at the sink	Surgery (excision and repairing the tendon)	Mature bone with fibrosis of the marrow space	15 mo	Good
	66	F	NA	-	+	-	Unspecified	Surgery (excision and repairing the tendon)	Mature bone with fibrosis of the marrow space	12 mo	Good
Weseley *et al*[11] (1976)	58	M	NA	-	+	-	None (spontaneous occurrence)	Nonoperative (immobilization for 6 wk)→Surgery (excision and transferring peroneus brevis)	Mature bone	3.5 mo	Nonoperative: poor; surgery: good
Brotherton and Ball[14] (1979)	71	M	12.5 cm	+	-	-	Walking uneven ground	Surgery (reduction and holding with a figure of eight wire)	Partly woven and partly lamellar bone, forming a cancellous structure	4 mo	NA
Fink and Corn[8] (1982)	42	F	8 cm	-	-	Hypertension, hypothyroidism, obesity	Stumbling on level ground	Surgery (excision and reconstruction with gastrocnemius fascia flap)	NA	4 mo	Good
Kernohan and Hall[17] (1984)	64	M	20 cm	-	-	Manual worker	NA	Surgery (Achilles tendon graft interposition)	NA	5 mo	Good
Suso *et al*[16] (1988)	20	M	10 cm	-	-	Long-distance runner	Long-distance run	Surgery (excision and direct repair)	Bony trabeculae, separated by fibrous tissue areas	3 mo	Good
Resnik and Foster[10] (1990)	36	M	NA	-	+	-	Stepping in a hole	Nonoperative (immobilization for 6 wk)→Surgery (excision and reconstruction with tensor fascia lata graft)	NA	NA	Nonoperative: poor; surgery: good
Friedman[13] (1991)	41	F	NA	+	-	-	Twisting the ankle	Surgery (excision, unspecified)	NA	NA	Good
Goyal and Vadhva[3] (1997)	84	M	6 cm	-	+	-	Crossing a road	Nonoperative (immobilization for 12 wk)	NA	12 mo	Good
Aksoy and Surat[6] (1998)	44	M	7 cm	+	-	-	Climbing upstairs	Surgery (excision and reconstruction with proximal Achilles tendon flap)	NA	24 mo	Good
Parton *et al*[5] (1998)	84	M	NA	-	+	-	Hurrying across a crossing	Nonoperative (immobilization for 8 wk)	NA	3 mo	Good
Haddad *et al*[15] (1999)	67	F	NA	-	-	Hypertension, obesity	Tripping in the garden	Nonoperative (immobilization for 6 wk)	NA	6 mo	Good
Mády and Vajda[2] (2000)	57	M	5 cm (bilateral)	-	-	History of treatment for clubfeet by serial plaster casts	None (spontaneous occurrence)	Surgery (interosseous polydioxanone suture which was reinforced by a local tendon flap)	Mature osseous tissue	84 mo	Good
Battaglia and	55	M	NA	+	-	Hypertension,	Strained while	Nonoperative (immobilization for 12	Osseous composition	6 mo	Nonoperative: poor;

Chandler[12] (2006)						dyslipidemia	pruning a tree	wk)→Surgery (excision and transferring flexor hallucis longus)			surgery: good
Ishikura *et al*[9] (2015)	50	F	14 cm	+	-	-	Climbing upstairs	Surgery (excision and reconstruction with hamstring tendon graft and gastrocnemius fascia flap)	Lamellar bone, which is covered by a number of osteoblasts in some areas	12 mo	Good
Gendera *et al*[18] (2020)	70	M	12 cm	-	+	-	None (spontaneous occurrence)	Surgery (excision and reconstruction with fascia lata graft)	Broad trabeculae of lamellar bone tissue with vital osteocytes	12 mo	Good

F: Female; M: Male; NA: Not available.

As for the patients who had no previous trauma or surgery, an obese person[15], a long-distance runner[16] and a manual worker[17] were included in the cases examined. The repetitive stresses from the overweight or overload might have led to the OAT. In that sense, repetitive stresses through obesity or an overactive state might be included in the concept of "previous trauma."

The mean period between the previous trauma or surgery and the occurrence of FOAT was 44.3 ± 20.8 years (n = 10, 15-78 years). This implies it takes a considerable amount of time for the ossification to grow big enough to fracture.

SIZE AND LOCATION OF THE OSSIFICATION

According to the previous reports about the OAT, a variety of sizes have been reported[4]. However, as for the FOAT, the length is 5 cm or more in all the mentioned cases[2,3,6,8,9,14,16-18].

OAT can occur in the body of the tendon or at its insertion into the calcaneus[1,4,6,14]. In the cases reviewed, the site of ossification could be detected by plain radiographs in 15 cases. The ossifications were located within the body of the tendon in 13 cases. In the remaining 2 cases, the ossification was present at the insertion of the calcaneus[12,15].

Considering these tendencies, ossifications in the body of the Achilles tendon that are > 5 cm long may have a higher risk of fracture. However, additional studies are needed to confirm this hypothesis.

CAUSE OF FOAT

In general, rupture of an unaffected Achilles tendon occurs in sports with abrupt repetitive jumping and sprinting activities[19]. By contrast, FOAT occurs without any trigger or with minimal trigger such as climbing upstairs and crossing a road[2,3,6,9,11,18]. This fact probably reflects the fragility of the OAT. This fragility may be attributable to

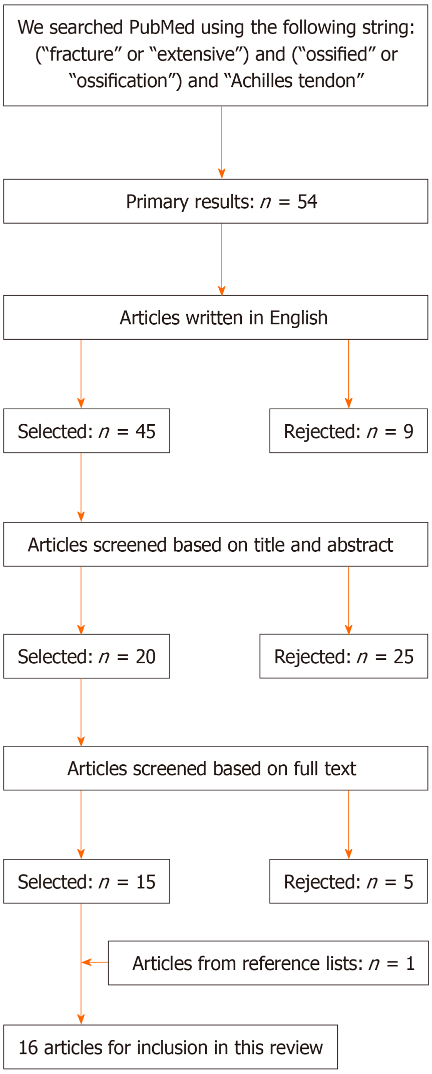

Figure 1 Search strategy for this study.

its histological structure described in the "Histology of FOAT" section.

DIAGNOSIS OF FOAT

Although an OAT is usually asymptomatic[10,12], it can sometimes cause pain if the inflammation exists around the ossified area[4]. Meanwhile, once the ossified mass fractures, it causes symptoms including severe local pain, swelling, and weakness of plantar flexion[10,12]. Therefore, if the patients with an OAT suddenly experience pain, a fracture should be suspected[14].

As for the physical examination, it should be noted that Thompson calf squeeze test is sometimes negative despite the presence of the fracture[12,17]. It is probably because of the retained continuity of Achilles tendon component around the fractured ossification. Therefore, plain radiographs should be used to obtain precise diagnosis. Magnetic resonance imaging is also used to evaluate the hemorrhage, edema, and soft tissue condition around the fracture site[5,9].

TREATMENT OF FOAT

According to previous reports, FOAT is treated either nonoperatively or surgically. In elderly patients, the nonoperative treatments are one of the options, because it can bring satisfactory results in some cases[3,5,15]. However, in 3 cases of younger patients, it has not produced the desired functional outcome. Resnik and Foster[10] reported a case of a 36-year-old man who underwent nonoperative treatment for FOAT but experienced persistent pain and swelling even after the treatment. He eventually underwent surgical excision of the bony mass and tendon reconstruction. Weseley *et al*[11] and Battaglia and Chandler[12] reported similar cases of male patients in their 50s who experienced failure of the nonoperative treatment modality and, subsequently, underwent the surgical treatment. Given these results, only limited outcomes should be expected from nonoperative treatment modalities, particularly in younger patients.

The surgical procedures for the treatment of the FOAT include internal fixation[2,14] and excision of the fractured mass, followed by the reconstruction with autografts[6,8-10,18] or adjacent tendon transfer[11,12]. Although internal fixation of the fractured mass reportedly offers the prospect of bone union[2,14], the applicable cases should be limited because this treatment does not eradicate the risk of non-union and refracture. Meanwhile, when the fractured mass was excised, diverse procedures have been conducted to cover the defect. If the ossification does not involve all layers of the Achilles tendon, direct repair of the tendon could be applicable[1,16]. However, if the ossification has infiltrated almost all layers of the tendon and there is a defect after excision, various kinds of grafts including gastrocnemius fascia turndown flap, hamstring tendon and tensor fascia lata grafts have been used to cover the defect[6,8-10,18]. For the adjacent tendon transfer, the peroneus brevis and flexor hallucis longus tendons have been used[11,12].

These procedures of reconstruction are also performed to treat chronic Achilles tendon ruptures[20-23].

HISTOLOGY OF FOAT

Ossification, not calcification, typically accounts for a great majority of patients with Achilles tendon mineralization[4]. This tendency is consistent with our FOAT cases. All the patients whose histological appearances were available in this study showed bone tissues instead of calcification[1,2,9,11,12,14,16,18]. Lamellar bone, or combination of lamellar bone and woven bone was reported. In one of the cases examined here, histological sections stained with hematoxylin and eosin revealed that the tendon tissue underwent cartilaginous metaplasia and was gradually replaced by lamellar bone, which is surrounded by a number of osteoblasts[9]. These histological findings suggest the occurrence of endochondral ossification, which is consistent with the observation of heterotopic ossifications in other studies[24,25]. In that sense, histology of FOAT is quite similar to that of the heterotopic ossification. However, in our FOAT cases, the bone structures are often separated by fibrous tissues[1,16]. Such a mixed structure may be responsible for its fragility and this might be the distinct feature of FOAT. Given this histological finding, leaving the ossified mass in the FOAT patients may entail the risk of refracture. Therefore, the fundamentals of treating FOAT should include excision of the ossified mass as much as possible, followed by repairing or reconstructing the tendons. Past studies also reported the cases describing the combination of endochondral and intermembranous ossification[26,27]. However, the exact mechanism of the ossification in the FOAT patients were not suggested in many cases. Further studies are needed to accumulate the histological findings and elicit the exact mechanism of the ossification and its fracture.

CONCLUSION

This review provides an overview of the FOAT. Many of the affected patients had a history of previous surgery or trauma. This fracture is distinct in that it occurs without any triggers or with minimal triggers. Nonoperative treatments offer only limited effects and surgeries are often performed. When the fractured mass was excised, repairing the tendon is applicable if the remnant is enough. If there is a defect after the excision, reconstruction with autografts or adjacent tendon transfer is performed. Treated properly, the functional result will be satisfactory.

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ORIGINAL ARTICLE

Basic Study

Osseointegration of porous titanium and tantalum implants in ovariectomized rabbits: A biomechanical study

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Abstract

BACKGROUND

Today, biological fixation of uncemented press-fit acetabular components plays an important role in total hip arthroplasty. Long-term stable fixation of these implants depends on the osseointegration of the acetabular cup bone tissue into the acetabular cup implant, and their ability to withstand functional loads.

AIM

To compare the strength of bone-implant osseointegration of four types of porous metal implants in normal and osteoporotic bone in rabbits.

METHODS

The study was performed in 50 female California rabbits divided into non-ovariectomized (non-OVX) and ovariectomized groups (OVX) at 6 mo of age. Rabbits were sacrificed 8 wk after the implantation of four biomaterials [TTM, CONCELOC, Zimmer Biomet's Trabecular Metal (TANTALUM), and ATLANT] in a 5-mm diameter defect created in the left femur. A biomechanical evaluation of the femur was carried out by testing implant breakout force. The force was

gradually increased until complete detachment of the implant from the bone occurred.

RESULTS
The breakout force needed for implant detachment was significantly higher in the non-OVX group, compared with the OVX group for all implants (TANTALUM, 194.7 ± 6.1 N *vs* 181.3 ± 2.8 N; P = 0.005; CONCELOC, 190.8 ± 3.6 N *vs* 180.9 ± 6.6 N; P = 0.019; TTM, 186.3 ± 1.8 N *vs* 172.0 N ± 11.0 N; P = 0.043; and ATLANT, 104.9 ± 7.0 N *vs* 78.9 N ± 4.5 N; P = 0.001). In the OVX group, The breakout forces in TANTALUM, TTM, and CONCELOC did not differ significantly (P = 0.066). The breakout force for ATLANT in the OVX group was lower by a factor of 2.3 compared with TANTALUM and CONCELOC, and by 2.2 compared with TTM (P = 0.001). In the non-OVX group, the breakout force for ATLANT was significantly different from all other implants, with a reduction in fixation strength by a factor of 1.9 (P = 0.001).

CONCLUSION
TANTALUM, TTM, and CONCELOC had equal bone-implant osseointegration in healthy and in osteoporotic bone. ATLANT had significantly decreased osseointegration (P = 0.001) in healthy and in osteoporotic bone.

Key Words: Animals; Bone-implant interface; Osteoporosis; Femur; Tantalum; Titanium

Core Tip: In an *in vivo* model of osteoporosis, it was found that some types of porous acetabular components are more compatible with osteoporotic bone. The study results can help to select the right choice of acetabular components for hip replacement in patients with low bone mass.

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followed. The *in vivo* study was approved by the Ethical Clearance Bioethics Committee State Institution "Sytenko Institute of Spine and Joint Pathology NAMS of Ukraine", Kharkiv, Ukraine (Protocol No. 175 of 26 Feb 2018).

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INTRODUCTION

Today, biological fixation of uncemented press-fit acetabular components plays an important role in total hip arthroplasty. Long-term stable fixation of these implants largely depends on the osseointegration of bone tissue into the acetabular cup implant and their ability to withstand functional loads[1,2].

It has been established that both the implant surface and the condition of bone tissue are of great importance in the process of osseointegration[3]. Implant qualities including structure, strength, stiffness, porosity, coefficient of friction, and surface roughness have significant impact on the quality and quantity of bone osseointegration as well as the long-term survival of press-fit implants[4,5]. In patients with osteopenia and osteoporosis, both qualitative and quantitative properties of bone tissue deteriorate, leading to a weakening of bone metabolism that then leads to accelerated osteoclastogenesis and bone resorption[6,7]. The above situation is an unfavorable condition for the implantation of uncemented press-fit acetabular components[8].

In a previous experimental animal study utilizing a rat model, it was shown that osseointegration of current porous acetabular implant materials, as well as the possibility of successful implantation and osseointegration in osteoporotic bone, directly depends on the structural characteristics of the porous implant[9]. However, there is a lack of comparative data of the strength and stability of the bone-metal osseointegration of current porous materials used in acetabular components in both normal and in osteoporotic bones.

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The study aim was to carry out a comparative analysis of the strength of the formed bone-metal osseointegration among four types of porous metal implants in an *in vivo* animal model with both normal bone and after the simulation of osteoporosis. Our hypothesis was that there will be a difference in the strength between the formed bone metal osseointegration between normal and osteoporotic bone models.

MATERIALS AND METHODS

Animals

Fifty female California rabbits 6 mo of age and weighing 4.5-5.0 kg) were kept in conditions of 24 °C, 12/12 h light/dark, and 60% humidity, with *ad libitum* access to food and water, and a standard diet. All surgeries (ovariectomy and implantation of materials) were performed under general intramuscular anesthesia (xylazine hydrochloride 15 mg/kg and ketamine 50 mg/kg). Euthanasia was carried out by overdosing of ketamine (50 mg/kg) and subsequent air embolism. All experiments were performed according to the national guidelines and all appropriate measures were taken to minimize pain or discomfort to the animals. The study design was approved by the local Bioethics Committee.

Study design

Rabbits were randomly divided into healthy control non-ovariectomized (non-OVX) and ovariectomized (OVX) groups of 25 each. To simulate osteoporosis, ovariectomy was performed in the OVX group. After 3 mo, 10 rabbits (5 non-OVX and 5 OVX) were sacrificed to confirm of osteoporosis development. For the remaining rabbits, (n = 40) one of the four types of porous materials were implanted. All rabbits with implants were sacrificed 8 wk after implantation.

Implants

The four types of implants used in this study were of comparable 80% or greater porosity. Three were Ti6-Al4-V titanium alloys: TTM (AK Medical, Beijing, China), CONCELOC (Smith & Nephew, Memphis, TN, United States), ATLANT (TITAN-MED, Kyiv, Ukraine). The fourth was porous Zimmer Biomet's Trabecular Metal (TANTALUM) (Zimmer, Warsaw, United States). The elastic moduli are 3 GPa for TANTALUM[10], 12.9 for GPa[11], 4.3 GPa for CONCELOC[12], and 113 GPa for ATLANT. A 1.2 mm diameter hole was drilled on one side of the implants to allow mounting of the testing jig. The testing jig that was attached to the implant was used to test breaking strength during the study (Figure 1A). Prior to implantation, the biomaterials were sterilized by autoclaving at 132 °C for 20 min.

Surgical procedures

Ovariectomy (n = 25) was performed under general anesthesia by two dorsolateral 2.5 cm incisions of the skin and muscles following the method described by Wanderman *et al*[13].

Implantation of materials: Each type of porous material was implanted in 5 healthy and 5 ovariectomized rabbits (n = 40) under general anesthesia under sterile conditions. The surgical field in the proximal part of the left femur was treated with Betadine antiseptic solution, after which the skin was incised from the lateral approach along the anterior femoral region above the greater trochanter. The musculus tensor fasciae latae and musculus quadriceps femoris were bluntly dissected and sequentially fixed. The greater trochanteric area was perforated by a burr to create a bone defect to match the biomaterial samples (diameter of 5 mm, length of 6 mm). After that, the wound was sutured in layers and the skin was treated with Betadine antiseptic. As postoperative pharmacological therapy, benzylpenicillin, dihydrostreptomycin (combikel 40) and meloxicam were administered.

X-ray radiographic evaluation

Radiographic evaluation was performed three times. Three months after ovariectomy to control osteoporosis development in 5 OVX and 5 non-OVX rabbits, immediately after implantation to evaluate the position of implants, and at 8 wk after implantation for all 20 OVX and 20 non-OVX rabbits (Figure 2). In all cases, a digital X-ray diagnostic system (OPERA T90cex; General Medical Merate S.p.A., Italy) was used.

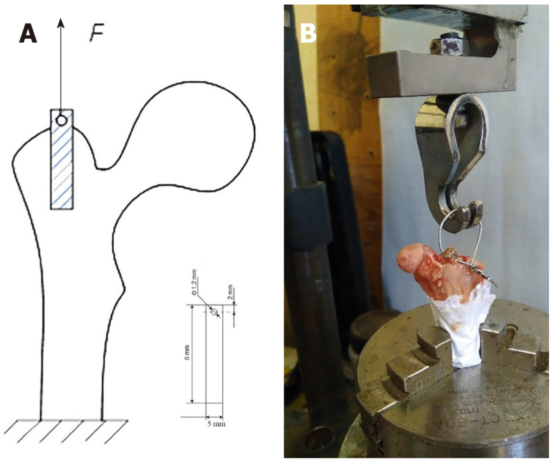

Figure 1 Scheme of biomechanical testing and biomechanical testing. A: The geometric dimension of the implants; B: Rabbit femur with implant on the stand during testing.

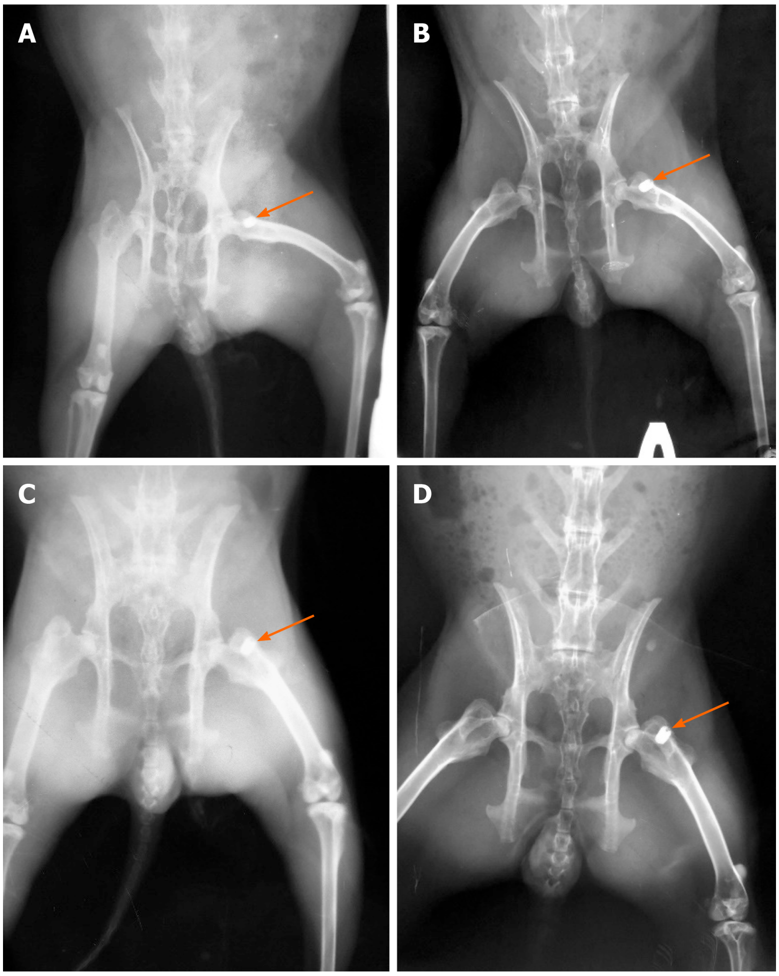

Figure 2 X-ray images of rabbits after implanted CONCELOC material (arrow) in the proximal femur. A: Non-ovariectomized (non-OVX) rabbit after surgery; B: Non-OVX rabbit at 8 wk after surgery; C: Ovariectomized (OVX) rabbit after surgery; D: OVX rabbit at 8 wk after surgery.

The analysis of cortical thickness index

Radiographs of the femur was obtained in 10 rabbits (5 OVX and 5 non-OVX) before implantation of materials to verify the osteoporosis model (Figure 3)[14]. This method is used as an alternative to measurement of bone mineral density in diagnosis of osteoporosis[14]. Using "X-Rays" software (Kharkiv National University of Radioelectronics, Ukraine)[15,16], the cortical thickness index was automatically

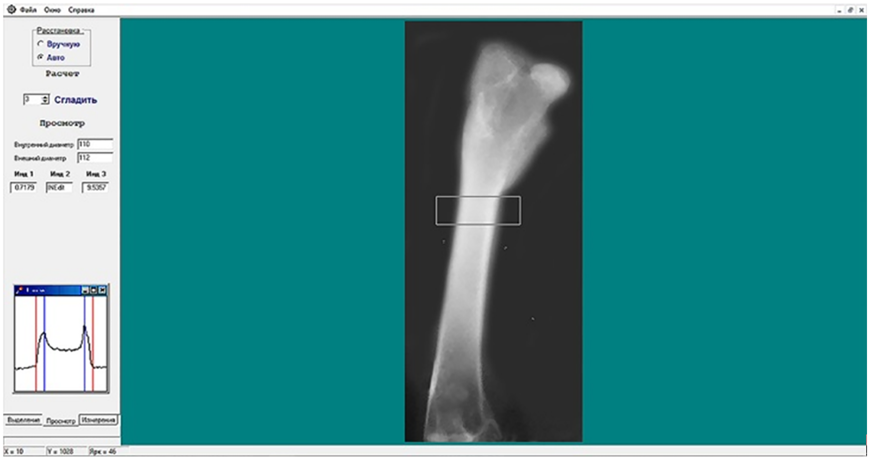

Figure 3 Evaluation of the cortical thickness index of the proximal femur of rabbit with "X-Rays" software (Kharkiv National University of Radioelectronics, Ukraine) 3 mo after ovariectomy.

calculated based on the measurement of the thickness of the cortical layer of the femur under the lesser trochanter in 10 rabbits. This software allows performing a coordinate-brightness analysis of digital radiographs, and provides spatial sampling with 0.042 mm elements and brightness quantization with a grayscale of 256 intensities. The analysis was performed by two independent experts.

Biomechanical testing

The implanted materials were rigidly fixed to the testing jig and breakout force testing was performed to detach the implant from the bone tissue (Figure 1B). We applied a breakout force to the implant at a constant speed of 1 mm per minute, which was gradually increased until complete detachment of the implant from the bone. The maximum value of the breakout force (N) was recorded with a strain gauge (SBA-100L) and a CAS type CI-2001A registration device (South Korea) (Figure 4).

Statistical analysis

Data were reported as means ± SD. Unpaired *t*-tests were used to evaluate the effect of osteoporosis on the stability of the same type of implant. Unpaired *t*-tests were performed for verification of osteoporosis model. To analyze the effect of the type of material on the strength of osseointegration in the non-OVX and OVX groups, one-way analysis of variance (ANOVA) was carried out with the post-hoc Duncan test. The critical level of significance was accepted as 0.05. The analysis was performed with IBM SPSS Statistics 19.0 software. The statistical methods were reviewed by Olena Karpinska and Michael Karpinsky of the Department of Biomechanics, Sytenko Institute of Spine and Joint Pathology, National Academy of Medical Sciences of Ukraine.

RESULTS

Analysis of cortical thickness index

In the OVX group (n = 5), the cortical thickness index of the proximal femur was 1.4 times lower (P = 0.001) than that in the non-OVX group (n = 5) (0.482 ± 0.033 *vs* 0.660 ± 0.007, unpaired *t*-test).

Biomechanical testing

Data were obtained on the maximum breakout force that led to detachment of the implant from the femoral bone in both normal and osteoporotic bone tissue. The strength of the implant attachment in the femoral bone tissue was significantly higher in non-OVX group (n = 20), compared with the OVX group (n = 20) for all materials (Figure 5, unpaired *t*-test). When evaluating each implanted material, the breakout force was higher in the non-OVX group by a factor of 1.1 for TANTALUM (194.7 ± 6.1 N *vs* 181.3 ± 2.8; P = 0.005); CONCELOC (190.8 ± 3.6 N *vs* 180.9 ± 6.6 N; P = 0.019); and TTM (186.3 ± 1.8 N *vs* 172.0 ± 11.0 N; P = 0.043), and by a factor of 1.3 (104.9 ± 7.0 N *vs*

Figure 4 Device for recording breakout force with a strain gauge.

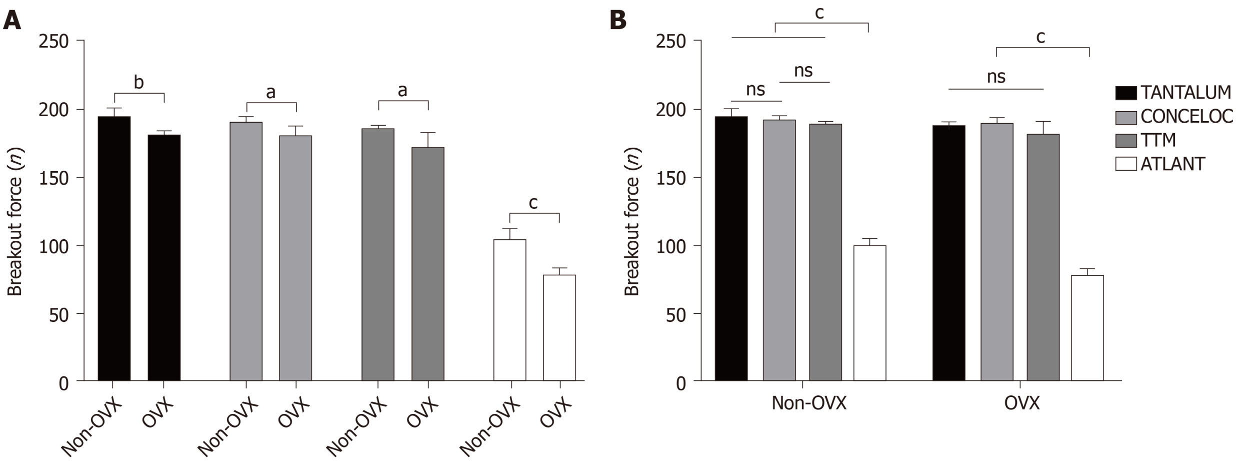

Figure 5 Results of breakout force testing of four types of porous materials in ovariectomized (OVX, *n* = 20) and healthy rabbits (non-OVX, *n* = 20) 8 wk after implantation. A: Unpaired *t*-test: Analysis of the effect of osteoporosis (OVX group) on the bone-implant strength and osseointegration for the same type of implant; B: ANOVA with post-hoc Duncan test evaluation of the effect of the implant material on bone-implant strength and osseointegration in ovariectomized and non-ovariectomized rabbits. $^aP < 0.05$; $^bP < 0.01$; $^cP < 0.001$. ns: not significant; non-OVX: non-ovariectomized; OVX: ovariectomized.

78.9 ± 4.5 N; *P* = 0.001) for ATLANT, compared with the OVX group.

TANTALUM implants had the highest breakout strength in osteoporotic bone tissue at a load of 181.3 ± 2.8 N and in normal bone tissue at a load of 194.7 ± 6.1 N (Figure 5). The lowest breakout strength was shown in ATLANT implants. Failure was observed in normal bone tissue at a load of 104.9 N ± 7.0 N and in osteoporotic bone at 78.9 ± 4.5 N. In the OVX group (osteoporotic bone), the breakout forces of TANTALUM, TTM, and CONCELOC did not differ significantly (*P* = 0.066, Figure 5, one-way ANOVA). On the contrary, The breakout force of ATLANT implants was lower by a factor of 2.3 compared with TANTALUM and CONCELOC and by a factor of 2.2 compared with TTM (*P* = 0.001). Results in the non-OVX group (normal bone) were similar to those in the OVX group with minor differences (Figure 5, one-way ANOVA). The breakout force for TANTALUM and CONCELOC implants did not differ significantly (*P* = 0.239). ATLANT implants were significantly different from all other implants, with a reduction in fixation strength of approximately 1.9 times (*P* = 0.001).

DISCUSSION

In this biomechanical study, we examined the strength of osseointegration of three porous titanium and one porous tantalum materials. We studied the breakout strength of the implanted materials 8 wk after their implantation in the metaphysis of the greater trochanter of the femur in an *in vivo* rabbit model. Three of the studied materials in this study (TANTALUM, CONCELOC, TTM) are used in the manufacture of acetabular components for total hip replacement and are currently used in clinical practice. The fourth studied sample (ATLANT) is a new material used in the manufacture of acetabular cups. A unique aspect of our study is the comparison of the breakout strength among the four studied materials in both normal and osteoporotic bone in a rabbit ovariectomy model.

The importance of bone quality for osseointegration of porous implants has been shown both in cadaver studies[17,18] and in an animal model[19]. Beckmann *et al*[18] reported the results of a biomechanical study (multi-axial testing machine) that examined the mobility of an acetabular titanium cup with a porous surface in 10 cadaveric pelvises. They found an inverse relationship between the bone mineral density (BMD) of the femoral neck and the mobility of the acetabular cup. Similar data were obtained when using an additional acetabular porous augment[18]. The differences in osseointegration and breakout strength between different commercial acetabular cup materials are especially important in patients with low BMD. It has been found that patients with low BMD have an increased risk of migration of uncemented hydroxyapatite-coated titanium alloy acetabular cups 3–12 mo after total hip arthroplasty (THA) compared with patients with normal BMD[8]. According to a clinical study of 283 patients evaluated 2 years after revision THA, it was found that porous tantalum acetabular cups were more stable than porous titanium cups in patients with low BMD[20]. However, the long-term survivorship of acetabular cups in patients with osteoporosis is poorly understood in comparison with patients with normal BMD[21].

According to our data, the stability of implants in the OVX group was lower for all materials studied compared with the non-OVX group. Similar results were obtained by Fujimoto *et al*[19] when evaluating titanium implants in an experimental model of glucocorticoid-induced osteoporosis in rabbits. Similar to our results of the non-OVX group, Duan *et al*[22] presented biomechanical testing (push-out test) of medical Ti-6Al-4V substrates with titanium and tantalum coated implants. Their results showed that at 9 wk after implantation, the titanium and tantalum implants had similar push-out strengths when evaluated in New Zealand white rabbit femurs.

Our findings of similar breakout forces in tantalum (TANTALUM) and titanium implants (TTM and CONCELOC) in the OVX group may have occurred because the evaluated titanium implants had similar porosity, highlighting the importance of high porosity percentage in these implants. It has been shown that high porosity improves osseointegration compared to nonporous implants[23,24]. Pore size is also an important factor affecting osseointegration of the implant[23,24]. These variables probably explain the lower values of breakout force exhibited by the ATLANT component material compared with the other implants in both OVX and non-OVX models. A recent study in rabbits that compared titanium implants manufactured by additive technology and with three different pore sizes (500 μm, 700 μm and 900 μm)[25] showed that the best interfacial strength was achieved when the pore size was 700 μm, when evaluated by a push-out test at weeks 4 and 12 after implantation. This emphasizes the importance of the material pore size for its osseointegrative qualities. This knowledge may help manufacturers design materials made with similar technology and from different alloy materials. Nevertheless, when comparing tantalum and titanium implants with the same 500 μM pore size and 70% porosity in a rabbit model, the authors did not find any differences in the push-out test indices at 2 wk, 4 wk, and 8 wk after implantation[26]. The same results were reported in a similar study by Su *et al*[27] when comparing tantalum and titanium implants with the same pore size.

A limitation of our study was the use of one type of test to evaluate implant stability. However, our study is one of the few studies comparing tantalum and titanium materials in a low bone-mass model. Thus, these results will help expand the current knowledge of the stability of the studied materials in cases of osteoporosis.

CONCLUSION

TANTALUM, TTM and CONCELOC had equal bone-implant osseointegration in both healthy and osteoporotic bones. ATLANT showed a significant decrease in osseointegration (P = 0.001) in both healthy and osteoporotic bone.

ARTICLE HIGHLIGHTS

Research background

Highly porous metal acetabular components are widely used in patients with low bone mass, but the strength of osseointegration may differ.

Research motivation

There is a need to perform studies to compare the strength of osseintegration of new porous metal biomaterials used in total hip arthroplasty of patients with low bone mass.

Research objectives

The objective of this study was to compare the strength of the formed bone-metal osseointegration among four types of porous metal biomaterials in an *in vivo* animal model with both normal bone and after simulation of osteoporosis

Research methods

The experimental study was performed in a rabbit model of postmenopausal osteoporosis. Biomechanical evaluation of the femur was carried out by testing the implant breakout force 8 wk after implantation of four types of biomaterials: TTM, CONCELOC, Zimmer Biomet's Trabecular Metal (TANTALUM), and ATLANT. The force was gradually increased until complete detachment of the implant from the bone.

Research results

The breakout force needed for implant detachment was significantly higher in healthy controls, compared with the ovariectomized group for all implants. The breakout force for ATLANT in the ovariectomized group was lower than that observed with TANTALUM, CONCELOC' and TTM.

Research conclusions

TANTALUM, TTM and CONCELOC had equal bone-implant osseointegration in healthy and osteoporotic bones. ATLANT showed a significant decrease in osseointegration in healthy and osteoporotic bone.

Research perspectives

Further studies on the use of other biomechanical methods will expand the knowledge of the strength of osseointegration of modern porous materials, which will help in choosing optimal materials for acetabular implants when performing total hip arthroplasty in patients with osteoporosis.

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ORIGINAL ARTICLE

Retrospective Study

Predictors of clinical outcomes after non-operative management of symptomatic full-thickness rotator cuff tears

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Abstract

BACKGROUND

Previous studies have shown that non-surgical management can be an effective treatment strategy for many patients with rotator cuff tears. Despite the prevalence of rotator cuff disease, few studies have examined the patient and tear related factors that predict outcomes of nonsurgical management in this cohort of patients.

AIM

To identify factors that are associated with changes in patient reported outcomes over time in individuals with full-thickness rotator cuff tears treated without surgery.

METHODS

A cohort of 59 patients who underwent non-surgical management of full thickness rotator cuff tears with a minimum of 1-year follow-up were identified from our institutional registry. Patient demographics, comorbidities and tear characteristics were collected at initial presentation. Outcome measures were collected at baseline and at each clinical follow-up, which included Western Ontario Rotator Cuff (WORC) index, American Shoulder and Elbow Surgeons score, Visual Analog Scale for pain and Single Assessment Numerical Evaluation. Multi- and univariate regression analyses were used to determine the impact of each patient and tear related variable on final WORC scores and change in WORC scores throughout the study.

RESULTS

In this non-surgical cohort, all patient-reported outcome measures significantly improved compared to baseline at 1 and 2-year follow-up. There was no significant difference in outcomes between 1 and 2 years. The average improvement surpassed the published minimal clinically important differences values for WORC, American Shoulder and Elbow Surgeons, Visual Analog Scale pain and Single Assessment Numerical Evaluation scores. Regression analysis identified female gender (β = - 19.88, *P* = 0.003), smoking (β = -29.98, *P* = 0.014) and significant subscapularis fatty infiltration (β = -15.35, *P* = 0.024) as predictors of less favorable WORC scores at 1 year, and female gender (β = -19.09, *P* = 0.015) alone as a predictor of lower WORC scores at 2 years. Patients with symptom duration greater than 1 year at presentation reported less improvement in WORC scores at 1-year follow-up (β = -14.63, *P* = 0.052) and patients with traumatic tears reported greater improvements in WORC scores at 2-year follow-up (β = 17.37, *P* = 0.031).

CONCLUSION

Patients with full thickness rotator cuff tears can achieve and maintain clinically meaningful benefit from non-surgical management through 2-year follow-up. Female patients, smokers, and those with significant subscapularis fatty infiltration tend to have lower overall WORC scores at 1-year follow-up, and females also have lower WORC scores at 2-year follow-up. Patients presenting with symptoms greater than 1 year had less clinical improvement at 1-year follow-up, and those with traumatic tears had greater clinical improvement at 2-year follow-up.

Key Words: Rotator cuff tear; Conservative treatment; Patient reported outcome measures; Shoulder injuries; Shoulder pain

Core Tip: This clinical study examines the factors, both patient and tear-related, that predict patient reported outcome measures in a cohort of 59 patients with symptomatic, full-thickness rotator cuff tears who are treated non-surgically. All patients included in this study presented with magnetic resonance imaging scans which were used to measure several important characteristics including tear size, associated fatty infiltration and the supraspinatus tangent sign. Linear regression analyses were performed to determine which factors independently predicted patient reported outcome measures.

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INTRODUCTION

Rotator cuff disease represents the most common etiology of shoulder dysfunction in the aging population, with an estimated 4.5 million physician office visits annually in the United States dedicated to its treatment[1,2]. The prevalence of rotator cuff disease increases with age, with over 60% of patients over the age of 80 exhibiting evidence of rotator cuff pathology[3]. Despite its prevalence, the ideal management of full-thickness rotator cuff tears has yet to be clearly defined. There have been several randomized controlled trials comparing surgical and non-surgical management of rotator cuff tears with conflicting results supporting both treatment options[4-6]. Although non-surgical management does not lead to rotator cuff healing, it has been shown to be an effective treatment option in many patients, leading to improvements in function and patient-reported outcomes[7-11].

Despite the generally positive outcomes, few studies have investigated the factors that predict outcomes after non-surgical management of rotator cuff tears. The Multicenter Orthopaedic Outcomes Network (MOON) shoulder group identified patient expectations related to physical therapy, smoking status and activity level to be predictive of outcomes in their prospective cohort of patients with full thickness rotator cuff tears[12]. Boorman *et al*[13] found that only the rotator cuff quality-of-life index predicted treatment failure in their non-surgical cohort. Both of these studies defined treatment failure as patients who decided to undergo surgical intervention.

The objective of this study was to identify patient characteristics at initial presentation that might be predictive of patient-reported outcomes after non-surgical management of full thickness rotator cuff tears.

MATERIALS AND METHODS

Patient enrollment

This study was approved by our institutional review board. Patients who presented to our institution between 2009 and 2015 with full thickness rotator cuff tears were prospectively enrolled into our research registry. The inclusion criteria for this registry included patients at least 18 years old who were diagnosed with a full thickness rotator cuff tear proven by magnetic resonance imaging (MRI) or ultrasound. Exclusion criteria included patients with isolated subscapularis tears, those with a history of prior ipsilateral shoulder surgery, fracture, dislocation, infection, inflammatory joint disease, or those who had already undergone more than 4 wk of formal non-operative treatment modalities.

Baseline demographic data were obtained, including factors pertinent to rotator cuff pathology [age, sex, body mass index (BMI), smoking, diabetes]. Patients documented whether their symptoms were related to an injury (traumatic *vs* atraumatic) and how long their symptoms had been present. For the purpose of our analysis, symptom duration was categorized as less than 1 year and greater than 1 year.

Treatment allocation was determined by shared decision making between the surgeon and patient after a thorough clinical exam and discussion of the risks and benefits of operative and non-operative management. No specific criteria were formally utilized to determine the treatment arm, as each decision was individualized for the specific patient. A previous study by Kweon *et al*[14] analyzed this same patient registry and found that there were some patient factors which predicted allocation to surgical management, including younger age, lower BMI and duration of symptoms less than 1 year. Other relevant factors including sex, tear size, functional comorbidity score or any patient reported outcome measure were no predictive of treatment allocation in this same study. Patients who chose to pursue non-operative management in this registry were enrolled in formal physical therapy with a standardized rotator cuff rehabilitation protocol. This therapy involved shoulder stretching, rotator cuff resistance band strengthening and scapular stabilizing exercises. These patients were also treated with anti-inflammatory medications and occasional steroid injections as needed for pain control.

We identified 151 patients in the registry who underwent non-operative management with a minimum of 1-year follow-up. Fifty-nine of these patients had adequate pre-treatment imaging studies to evaluate rotator cuff muscle grading. Forty-three of the patients were followed for 2 years and the remaining 16 patients had 1 year of follow-up. Of note, there were a total of 316 patients in the registry treated for rotator cuff tears during this study period, signifying that 47.8% (151/316) of the total patients were treated non-operatively.

Patient-reported outcome measures

Upon enrollment into the registry, patients completed a demographic questionnaire as well as several patient-reported outcome measures including the Western Ontario Rotator Cuff (WORC) index[15], American Shoulder and Elbow Surgeons (ASES) score[16], Single Assessment Numerical Evaluation (SANE)[17] and Visual Analog Scale for pain[18]. The WORC index was used as the primary outcome measure for this study as it was developed and validated specifically for patients with rotator cuff tears[19]. The normalized version of the WORC index (WORCnorm) was utilized for this study, which converts the scores to a 0-100 point scale, with 100 representing the highest possible score. Outcome measures were collected at 6 and 12 mo, then at annual intervals. For the purpose of our study, the patients' last documented outcome measures (either 1 or 2 years) were used as their final outcome.

MRI evaluation

All patients included in this study underwent an MRI with at least a 1.5T magnet. These MRI studies all included a T1 sagittal oblique sequence which was used to evaluate the rotator cuff musculature. The maximal anterior-posterior and medial-lateral dimensions of the rotator cuff tear were multiplied to obtain the cuff tear index

(CTI)[20]. Of note, CTI was originally described using arthroscopic measurement techniques, but MRI based measurements were substituted in this non-surgical cohort. Fatty infiltration was graded on a scale of 0 to 4 as originally described in a computed tomography study by Goutallier *et al*[21]. Sagittal oblique T1 sequences were used to calculate the grade of fatty infiltration, as described in a subsequent MRI based study by Fuchs *et al*[22]. For the purpose of analysis, fatty infiltration was grouped by grades 0 and 1 *vs* grade 2 and higher. The supraspinatus tangent sign was also measured on this sequence, in accordance with the methods proposed by Zanetti *et al*[23]. MRI analysis was performed independently by two orthopaedic surgery sports medicine fellows, and any discrepancies between graders were resolved by an additional assessment performed by the senior author. Both inter-rater and intra-rater reliability were also assessed for this dataset and published previously by Naimark *et al*[24].

Statistical methods

Descriptive and inferential statistics were analyzed using Statistic Package for Social Science v22.0 (IBM) and STATA/MP 14.2. Differences in patient reported outcome measures at each time point were obtained using univariate analysis of variance post-hoc testing using Tukey's test was utilized to check for significant differences between specific time points. P values less than 0.05 were considered significant. Baseline demographic data are presented as the mean ± SD or a percentage within groups. An a priori power and sample size analysis using a moderate effect size estimate was calculated and produced a requirement of 21 patients for a power of 0.80 at 95%CI.

Linear regression analyses were conducted for all continuous dependent variable, change in the WORC score and total normalized WORC scores at 1 and 2-year follow-up. Predictor variables included gender, age, BMI, smoking status, diabetes, CTI, traumatic or atraumatic tears, duration of symptoms greater than or less than 1 year, tangent sign, infraspinatus fatty infiltration, and subscapularis fatty infiltration. Multivariable models were completed, then an elimination analysis was performed, removing the least significant variable each time before running the analysis again. This elimination analysis was continued until only statistically significant variables remained. P values less than 0.1 were considered significant.

RESULTS

Fifty-nine patients met the inclusion criteria for this study. The baseline characteristics of these patients are displayed in Table 1. All patient-reported outcome measures improved over the course of the study compared to baseline values, as shown in Table 2. Statistically significant improvements were noted between baseline and 1 year and between baseline and 2-year outcomes. There was not a statistically significant improvement in any patient reported outcome between 1 and 2 years (Figure 1).

Multivariable linear regression models using final WORC scores at 1 and 2 years as the clinical outcome measure are shown in Table 3. At 1-year follow-up, female gender, smoking and advanced subscapularis fatty infiltration were found to be predictive of worse WORC scores. These factors predicted fairly substantial decreases of nearly 20, 29 and 15 points respectively. At 2-year follow-up, only female gender remained predictive of worse scores, with a similar decrease of 19 points on the normalized WORC score.

In addition to analyzing final WORC scores, multivariable analyses were also performed using the overall change in WORC scores at 1 and 2 years compared to baseline values. These results are shown in Table 4. At 1-year follow-up, patients with chronic symptoms (> 1 year) were predicted to have significantly less improvement in WORC scores by nearly 15 points. At 2-year follow-up, patients with traumatic tears were predicted to have over a 19-point greater increase in WORC scores. Age was also found to be a significant predictor of worse WORC scores at 2-year follow-up, although not likely clinically significant with a β value of less than 1 point. The mean improvements in WORC score at 2-year follow-up for patients with traumatic *vs* atraumatic and acute *vs* chronic tears are shown in Table 5.

DISCUSSION

Few studies have examined the factors associated with positive patient-reported outcomes after non-surgical management of full thickness rotator cuff tears. In this

Table 1 Baseline characteristics

Baseline characteristics	
Age	63.85 ± 8.48
Male, *n* (%)	37 (62.71)
BMI	29.63 ± 5.58
CTI	4.77 ± 4.47
Diabetes, *n* (%)	5 (8.47)
Smoking, *n* (%)	4 (6.78)
Traumatic, *n* (%)	40 (67.8)
Duration > 1 yr, *n* (%)	17 (28.81)
Tangent sign, *n* (%)	21 (35.59)
Supra FI ≥ 2, *n* (%)	27 (45.76)
Infra FI ≥ 2, *n* (%)	21 (35.59)
Subscap FI ≥ 2, *n* (%)	20 (33.9)
ASES baseline	54.91 ± 20.85
SANE baseline	31.13 ± 25.39
WORCnorm baseline	46.05 ± 21.61
VAS pain baseline	50.13 ± 26.39

Except as noted, values are expressed as mean ± SD. BMI: Body mass index; CTI: Cuff tear index; FI: Fatty infiltration; ASES: American Shoulder and Elbow Surgeons score; SANE: Single Assessment Numerical Evaluation; WORC norm: Normalized Western Ontario Rotator Cuff index; VAS: Visual analog scale.

Table 2 Change in outcome scores

	Baseline	Final follow-up	Change
WORCnorm	46.05 ± 21.61	63.58 ± 25.6	17.53 ± 6.87
ASES	54.91 ± 20.85	70.1 ± 25.03	15.19 ± 6.77
SANE	31.13 ± 25.39	59.4 ± 29.45	28.27 ± 7.41
VAS pain	50.13 ± 26.39	29.17 ± 26.68	-20.96 ± 7.28

Values are expressed as mean ± SD; WORCnorm: Normalized Western Ontario Rotator Cuff index; ASES: American Shoulder and Elbow Surgeons score; SANE: Single Assessment Numerical Evaluation; VAS: Visual Analog Scale.

study, we demonstrated that clinical outcome measures in a selected population of patients were significantly improved at 1 year. These results were durable at 2 years, with no statistically significant change between the 1 and 2-year follow-up. The average improvements in WORC, ASES, SANE and Visual Analog Scale pain scores all surpassed their published minimal clinically important differences (MCID) at final follow-up[25-27].

These results are consistent with previously published literature regarding non-surgical management of rotator cuff tears. Patients treated non-operatively in the MOON shoulder cohort were noted to have improvements of 22.5, 29.2 and 23.7 points in the WORC, ASES and SANE scores respectively, at 12-wk follow-up[10]. These are comparable to our cohort's improvements of 17.5, 15.2 and 28.3 points on these same scales respectively.

Based on our multivariable regression analyses, female gender, smoking and significant subscapularis fatty infiltration were found to be predictors of worse clinical outcomes at 1-year follow-up in our primary outcome measure, the normalized WORC score. These variables were not only statistically significant, but also clinically significant with magnitude of change with β values ranging between 15 and 30 points (WORC MCID = 11.7). At 2-year follow-up only female gender remained a significant

Table 3 Multivariable regression elimination analysis and for change in Western Ontario Rotator Cuff index score at 1 year and 2 year

	β	*P* value	95%CI
1 yr			
Female gender	-19.88	0.003	-32.82 to -6.95
Smoking	-28.98	0.014	-51.9 to -6.05
Subscap FI ≥ 2	-15.35	0.024	-28.62 to -2.07
2 yr			
Female gender	-19.09	0.015	-34.26 to -3.92

WORC: Western Ontario Rotator Cuff index; FI: Fatty infiltration; CI: Confidence interval.

Table 4 Multivariable regression elimination analysis for change in Western Ontario Rotator Cuff index score at 1 year and 2 year

	β	*P* value	95%CI
1 yr			
Duration > 1 yr	-14.63	0.052	-29.4 to 0.13
2 yr			
Age	-0.82	0.08	-1.75 to 0.10
Traumatic	19.06	0.017	3.65 to 34.48

WORC: Western Ontario Rotator Cuff index; CI: Confidence interval.

Table 5 Change in Western Ontario Rotator Cuff index score at 2-year follow-up

	Mean	SD	95%CI
Traumatic	26.82	27.3	16.39 to 37.25
Atraumatic	9.45	19.06	-0.49 to 19.38
Duration < 1 yr	24.61	24.72	16.04 to 33.18
Duration > 1 yr	5.71	24.84	-11.01 to 22.44

WORC: Western Ontario Rotator Cuff index; CI: Confidence interval; SD: Standard deviation

predictor of WORC scores, suggesting smoking status and subscapularis fatty infiltration may not be as clinically important for determining long-term prognosis.

Female gender has been shown in several other studies to negatively affect pain and clinical outcomes scores after rotator cuff repair surgery, however to our knowledge the same has not been shown in non-surgical cohorts[28-30]. This result may be further explained by the lower baseline WORC scores in females *vs* males in our cohort (35.5 *vs* 52.7), as the subsequent regression analyses evaluating change in WORC scores did not find female gender to be a predictor of less improvement throughout the study.

Smoking has also been shown in several studies to be a risk factor for worse clinical outcomes and decreased healing rates after rotator cuff repair[31-33]. In contrast, a study by Dunn *et al*[12] found that non-smokers were actually more likely to fail non-operative management of rotator cuff tears, however treatment success was defined as avoidance of surgical intervention rather than patient reported outcome measures. There may have been some selection bias introduced into this study outcome as well, as surgeons may have been more willing to offer surgery to non-smokers.

Although patients with isolated full thickness subscapularis tears were excluded from this study, over 1/3 of the patients in our cohort (20/59) did exhibit grade 2 or higher fatty infiltration in the subscapularis, indicating an anterosuperior variant rotator cuff tear. These tears have been associated with worse clinical outcomes in surgical cohorts in previous studies, especially when associated with higher grades of

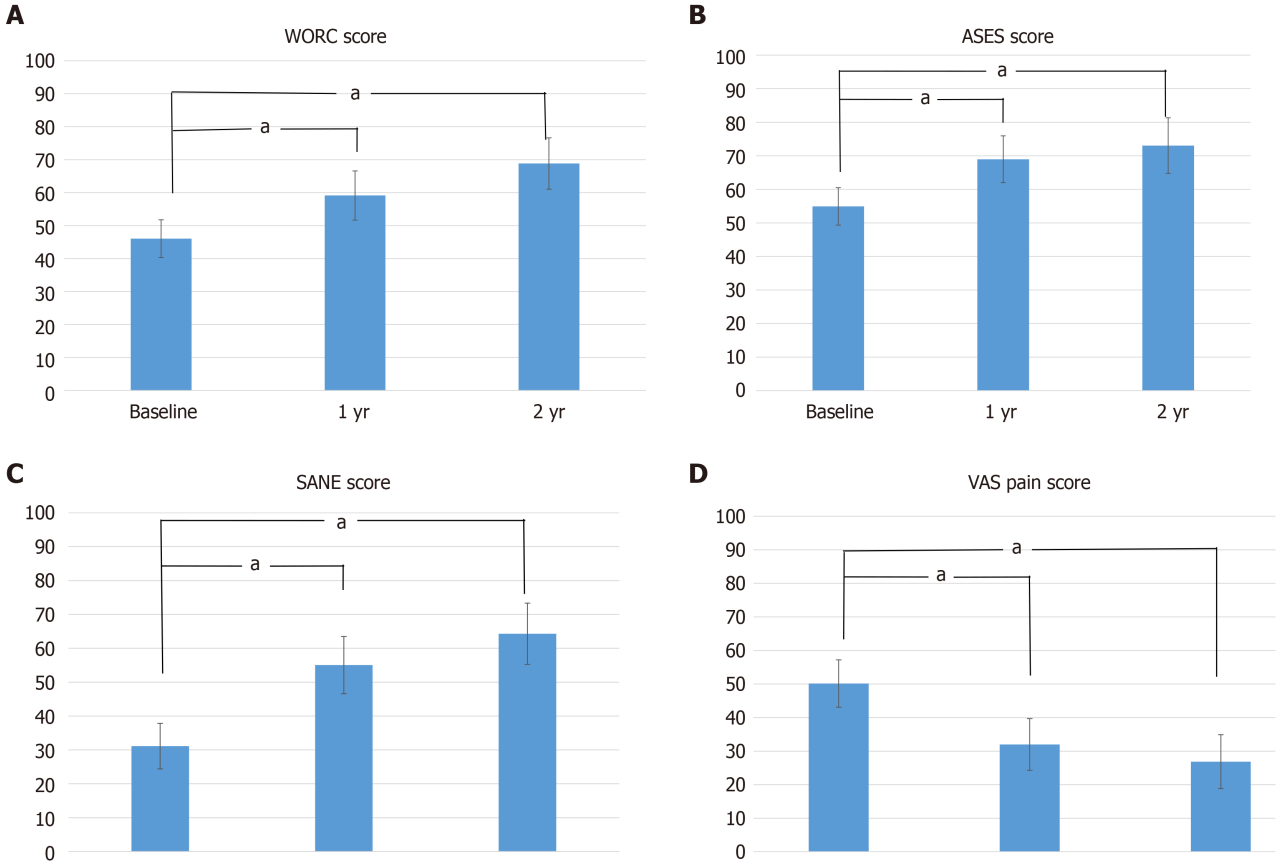

Figure 1 Patient-reported outcome measures. A: Western Ontario Rotator Cuff index; B: American Shoulder and Elbow Surgeons score; C: Single Assessment Numerical Evaluation; D: Visual Analog Scale. Indicates statistical significance ($^aP < 0.05$). WORC: Western Ontario Rotator Cuff index; ASES: American Shoulder and Elbow Surgeons score; SANE: Single Assessment Numerical Evaluation; VAS: Visual Analog Scale.

subscapularis fatty infiltration[34,35]. The results of our study mirror these results, with increased grades of subscapularis fatty infiltration portending worse WORC scores at 1-year follow-up.

In addition to the aforementioned factors that were predictive of final WORC scores in our study, we also analyzed the factors that impacted the amount of improvement patients achieved during the study period. We feel that both of these outcomes are worth examining, as they answer different clinical questions. Some patients may be more interested in the degree to which they will improve with a specific intervention rather than the final outcome they will achieve, and vice versa.

With this idea in mind, we performed additional regression analyses using the change in WORC score from baseline at 1 and 2-year follow-up as the clinical outcome measure. We found that patients presenting with symptom duration greater than 1 year achieved significantly less improvement at 1-year follow-up, and those with a traumatic onset of pain achieved significantly greater improvement at 2-year follow-up. Specifically, those with a traumatic onset of shoulder pain improved over 17 points more at 2-year follow-up than those with an atraumatic onset of pain, and those with symptoms less than 1 year at the onset of the study improved nearly 19-points more than those with symptoms greater than 1 year. Considering the MCID for normalized WORC scores has been published at 11.7 points, these variables predicted a fairly impactful magnitude of change.

The considerable effect of tear chronicity on improvement with non-surgical management may be explained by the idea that patients with long-standing symptoms have already gained some positive effects from some form of self-directed rehab, or simply by performing their day-to-day activities. These patients with chronic tears may have also developed some irreversible changes within their rotator cuff musculature, or within the glenohumeral joint itself due to altered mechanics. It is possible that these secondary changes may predispose them to worse outcomes with non-surgical management.

The explanation of the predictive impact of traumatic tears on the magnitude of improvement in this study is less clear. It may be theorized that patients with degenerative rotator cuff tears have a more diffuse underlying problem within the remainder of their intact cuff tendons, *vs* those who suffered acute traumatic tears. It may also be possible that there is an inherent difference in the population of patients who suffer a traumatic *vs* atraumatic tear, which may impact their ability to successfully rehab their ailing shoulders. Furthermore, there may be some overlap between tear mechanism and symptom duration at presentation. Specifically, those patients who sustain traumatic tears may be more likely to present for care acutely than those with an insidious onset of symptoms. An additional consideration is that while patients self-reported a traumatic onset of pain, many of these patients could have had pre-existing rotator cuff tears prior to these traumatic events. Their initial magnitude of symptom improvement may be related to resolution of pain related to temporary contusions or sprains related to these traumatic events. No pre-injury imaging studies exist in these patients to determine whether they truly suffered a traumatic rotator cuff tear, or simply trauma in the setting of an existing tear. These concepts warrant further investigation.

Several factors that have been identified as important predictors of outcomes in surgically managed rotator cuff tears, such as tear size, tangent sign, fatty infiltration in the posterosuperior cuff muscles, and diabetes, did not have an apparent impact on the outcomes of our non-surgical cohort[24,36,37]. Many of these factors may be related to tissue healing capacity, which presumably would be less critical in those patients being treated non-surgically. Other studies evaluating outcomes with non-operative management have also found these patient and tear related factors to be unrelated to clinical outcomes[12,13].

Our study was not without limitations. Although the data was collected prospectively, this study was retrospective in nature. Also, treatment allocation into this non-surgical cohort was not randomized. Patients had the ability to choose between surgical and non-surgical management, which could introduce some selection bias into the study. Outcomes of this cohort may not be entirely generalizable to all patients presenting with full thickness rotator cuff tears. The cohort included in this study was also smaller than other similar studies which included multiple centers, such as the MOON group studies[10,12]. Also, although many variables were included in the regression analyses as potential predictors of patient outcomes, other potentially significant factors may have been neglected, such as workers compensation status, tear retraction, or concomitant biceps tendon pathology. Also, standardized physical exam findings were not available for review, and could have impacted patient outcomes. Although fatty infiltration of the various rotator cuff muscles was used as a surrogate of tear location (*i.e.*, anterosuperior *vs* posterosuperior), the specific location and tendons involved in each rotator cuff tear were not specifically categorized, which may have affected the interpretation of these tear subtypes. Other limitations include the lack if information regarding patient compliance with physical therapy and the lack of any follow up imaging studies to assess progression of tear size or fatty infiltration. These morphologic characteristics may be important when considering the long-term outcomes in these patients.

CONCLUSION

This study demonstrated that non-operative management of full thickness rotator cuff tears results in clinically meaningful and statistically significant improvements in patient reported outcome measures at 2-year follow-up. Female gender, smoking and advanced subscapularis fatty infiltration were predictive of lower WORC scores at 1-year follow-up; only female gender was predictive of lower WORC scores at 2-year follow-up. Patients with symptom duration greater than 1 year at presentation were found to have less improvement in WORC scores at 1-year follow-up, and those with traumatic tears demonstrated significantly greater improvements at 2-year follow-up. These outcome measures and patient related factors can be used to counsel patients with rotator cuff tears who are contemplating their treatment options.

ARTICLE HIGHLIGHTS

Research background

Rotator cuff tears are extremely prevalent in the general population, and many patients with rotator cuff tears can be treated successfully without surgical intervention. Little data exists in the literature regarding patient and pathology related factors which predict the outcomes after nonsurgical management.

Research motivation

By evaluating the patient reported outcomes in a cohort of patients who underwent nonsurgical management for full-thickness rotator cuff tears, we hope to uncover important factors which may refine treatment indications for this subset of patients.

Research objectives

The objectives of this study were to evaluate the outcomes of nonsurgical management in patient with full thickness rotator cuff tears, and to identify patient and tear related characteristics which may predict outcomes. These findings could have a significant impact on the treatment of patients with rotator cuff tears in the future.

Research methods

Patients in our institutional registry who underwent nonsurgical management for full thickness rotator cuff tears were identified. Pre-treatment magnetic resonance imaging scans were evaluated for tear size and related muscle atrophy and fatty infiltration. Patient reported outcomes were evaluated at 1 and 2 years after treatment began and regression analyses were performed in order to identify any predictors of patient reported outcomes in this cohort.

Research results

Patient reported outcome measures improved significantly at 1 and 2 year follow up after nonsurgical management. Patients who presented with chronic symptoms showed less improvement in patient reported outcome scores, and those with traumatic tears were noted to make greater improvements over the course of the study.

Research conclusions

Patients with full thickness rotator cuff tears can achieve significant clinical improvement with nonsurgical management. Several factors may affect the amount of improvement they achieve, including the duration of their symptoms at presentation and the mechanism of their pain at the onset of symptoms. Additional factors likely exist that may impact patient outcomes in the setting of rotator cuff pathology.

Research perspectives

Future studies should consider additional factors that may be relevant in predicting outcomes in patients with rotator cuff tears including pertinent physical exam findings and concomitant shoulder pathology such as biceps tendon involvement. Prospective comparative studies of surgical and nonsurgical management will also help clarify the ideal surgical and non-surgical indications in this cohort of patients.

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SYSTEMATIC REVIEWS

Hanging up the surgical cap: Assessing the competence of aging surgeons

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Abstract

BACKGROUND

As the average age of surgeons continues to rise, determining when a surgeon should retire is an important public safety concern.

AIM

To investigate strategies used to determine competency in the industrial workplace that could be transferrable in the assessment of aging surgeons and to identify existing competency assessments of practicing surgeons.

METHODS

We searched websites describing non-medical professions within the United States where cognitive and physical competency are necessary for public safety. The mandatory age and certification process, including cognitive and physical requirements, were reported for each profession. Methods for determining surgical competency currently in use, and those existing in the literature, were also identified.

RESULTS

Four non-medical professions requiring mental and physical aptitude that involve public safety and have mandatory testing and/or retirement were identified: Airline pilots, air traffic controllers, firefighters, and United States State Judges. Nine late career practitioner policies designed to evaluate the ageing physician, including surgeons, were described. Six of these policies included subjective performance testing, 4 using peer assessment and 2 using dexterity testing. Six objective testing methods for evaluation of surgeon technical skill were identified in the literature. All were validated for surgical trainees. Only Objective Structured Assessment of Technical Skills (OSATS) was capable of distinguishing between surgeons of different skill level and showing a relationship between skill level and post-operative outcomes.

CONCLUSION

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A surgeon should not be forced to hang up his/her surgical cap at a predetermined age, but should be able to practice for as long as his/her surgical skills are objectively maintained at the appropriate level of competency. The strategy of using skill-based simulations in evaluating non-medical professionals can be similarly used as part of the assessment of the ageing surgeons' surgical competency, showing who may require remediation or retirement.

Key Words: Aging surgeon; Competency; Surgical skill; Surgeon retirement

Core Tip: A surgeon should not be forced to hang up his/her surgical cap at a predetermined age, but should be able to practice for as long as his/her surgical skills are objectively maintained at the appropriate level of competency. The strategy of using skill-based simulations in evaluating non-medical professionals can be similarly used as part of the assessment of the ageing surgeons' surgical competency, showing who may require remediation or retirement.

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INTRODUCTION

The aging surgeon has remained a contentious patient safety issue, as the average age of surgeons continues to rise. The number of physicians exceeding the age of 65 has more than quadrupled in almost 40 years, and surgeons are no exception[1]. Currently, 38% of surgeons working in Canada and over 46% of the surgeons in the United States are above the age of 55 and 16% of Canadian surgeons are over the age of 65[2-4]. When should an older surgeon stop operating? This becomes an important issue when we consider that the surgical profession is highly dependent on memory, sensory acuity, clinical decisiveness, technical skills and physical stamina; skills and abilities that may decrease with age.

Like all professionals, surgeons are fallible and vulnerable to the natural process of aging in which cognitive and physical skills experience a decline. The relationship between surgeon age and operative risk is controversial and uncertain, with some studies showing worse outcomes and some showing reasonable, or even better outcomes[3,5-7]. Even so, there are accounts of prominent older surgeons struggling with simple fine motor skills and clinical decision making; while various studies have demonstrated that senior surgeons have worse outcomes than their younger colleagues, suggesting surgeon age is an operative risk factor[2,8-12]. In the past two decades, more research has been dedicated to studying the aging surgeon and trying to find more effective ways to help surgeons experiencing age-related decline[8,13-15].

Although age has been identified as a possible occupation hazard in the surgical profession[9,10], other professions within the public sector have maintained a more proactive approach with their aging workforce. These strategies include enforcing strict certification and mandatory retirement. Currently, retaining certification in a surgical field is not as rigorous a process and retirement of surgeons remains largely at their discretion, relying on the assumption that they are fully capable of identifying their own cognitive and physical regression[1,2]. Both the American College of Surgeons (ACS) and American Medical Association (AMA) recognize the safety implications of the aging physician and surgeon; and have recommended practitioners aged 65 to 70 undergo voluntary physical examination and visual testing, in addition to peer-reviewed performance evaluation for re-credentialing[1,2]. Programs have been developed to assess the competence of aging surgeons and guide them depending on their incapacities or capacities[16,17]. However, no standardized approach to address age-related deterioration in surgeons exists at this time.

In order to address this issue, we performed a scoping review of well-established and accepted policies of testing for competency of aging non-medical professionals from the industrial workplace. In particular we sought to identify strategies used to determine competency that could be transferrable in the assessment of aging surgeons. In addition, we reviewed the present testing of senior surgeons by hospitals to determine if the testing specifically addresses the skills, other than knowledge, required to maintain their competency to perform surgery.

MATERIALS AND METHODS

In order to identify mandatory testing of non-medical professions, where cognitive and physical competency are necessary for public safety, we conducted scoping review of the literature in PubMed, EMBASE, Google Scholar and Google using the terms mandatory retirement, mandatory retirement testing, retirement, mandatory retirement ages, surgeon retirement. The Google search engine was used to locate websites describing these professions within the United States. The mandatory age and certification process, including cognitive and physical requirements, were reported for each profession.

Google Scholar and the Google search engines were used to search for current policies, at health institutions in the United States, that are being used to evaluate older physicians and surgeons with regard to their ability to provide safe and high-quality care. The search queries used were: Late career practitioner policy, late career practitioner, assessing late career practitioners, aging physician policy, and aging surgeon policy. These policies were described based on their objectives, candidates, examination procedures, and modification of privileges.

Methods for determining surgical competency currently in use or practice as well as those existing in the literature were identified. Licensing bodies and subspecialist certification boards were described, along with their use of Continuing Medical Education (CME) and Maintenance of Certification (MOC) as a means of assessment. These agencies were selected as they are invested in ensuring the clinical competency of practicing physicians for the welfare of the general public[18,19]. The published literature was reviewed for objective assessments of surgical technical skills that were shown to be valid and reliable, as well as predictive of surgeon competency and improved patient outcomes for surgeons. Studies were identified through a search of databases, including PubMed, EMBASE, and Google Scholar. Search queries were developed from the following keywords: Technical skill, surgery, assessment, surgical training, surgical skill. Objective assessment tools identified in the database search were described if studies evaluating these tools were written in English, evaluated participants performing surgical tasks, and analyzed the validity and reliability of the objective assessment. Review articles found were used to identify studies assessing the reliability and validity of the objective assessment tools. Virtual reality simulators were excluded as assessment tools as they are often used primarily to determine the validity and reliability of the performance tools in mock surgical procedures, rather than for assessment of surgical skills. All search queries were completed by May 20, 2020.

RESULTS

Non-medical professionals

Four non-medical professions requiring mental and physical aptitude that involve public safety and have mandatory testing and/or retirement were identified: Airline pilots, air traffic controllers, firefighters, and United States State Judges (Table 1). The nature of their work is such that any condition which compromises their competency, such as knowledge; cognition; illness or physical stamina; can put many members of the public at risk. As a result, these professions have mandatory retirement at specific ages, as well as strict recertification and licensing programs. A mandatory retirement age, which is different for each occupation, is enforced in all 4 professions. An annual medical exam is required for 3 of these professions; a skills refresher course and assessment in two of the professions; and a physical ability test in one to maintain the professional’s ability to continue working. These skill assessments, knowledge or physical, are designed to reflect the competency and proficiency standards of their profession. They entail simulated situations one may expect to encounter as part of their profession.

Table 1 Surgeon certification compared to non-medical professions

Occupation	Mandatory retirement age (yr)	Certification based on cognitive and/or physical requirements
Surgeon[33]	None	Complete residency and board examination. Continuous self-learning or medical education (CME) for credit with periodic examination for certification. May have case list peer-reviewed and be evaluated by in-hospital staff. No physical exam or performance-based skills currently defined
Airline pilot[34,35]	65	Every 24 mo, complete flight review with instructor: Ground/flight training. Must demonstrate proficiency, competency, and sound judgement within approved standards during training. Medical certificate every 12 mo or every 6 mo if age > 40 yr
Air traffic controller[36-38]	56, 61 with exception	Apply at < 31 yr. Medical exam. Pass biographical assessment, pass the ATSA, and pass training course at FAA academy. The ATSA is designed to measure the cognitive, visuospatial reasoning, and psychomotor abilities of candidates. Must submit to yearly physical exam, and job performance twice a year, with periodic drug screenings. Certificate valid until surrendered, suspended, or revoked
Firefighter[39,40]	57	Complete CPAT. Complete annual medical exam and physical testing, depending on department discretion. Physical testing consists of exercises related to firefighting such as step tests, and leg lifts
United States State Judge[41,42]	70-75	Obtained law degree and passed Bar examination. State court often requires mandatory retirement for state court judges

ATSA: Air traffic controller specialists skills assessment battery; CPAT: Candidate Physical Ability Test; CME: Continuing medical education; FAA: Federal Aviation Administration.

Late career practitioner policies

There are currently no mandatory retirement criteria for all surgeons in North America. We identified 9 late career practitioner policies designed to evaluate the ageing physician, including surgeons. One of the policies, the Aging Surgeon Program at Sinai Hospital, specifically targets the aging surgeons, but is identical to the Hospital's evaluation of medical doctors, and has no specific testing of surgical skills (Table 2). All nine of these policies vary according to their trigger for assessment, the assessments being utilized (medical exam and performance testing), and their influence on hospital privilege modification. Eight of the policies use age to identify physicians that require cognitive and physical testing, starting typically at the age of 70 years, with repeated testing required every 1 or 2 years. All 9 physician monitoring programs have a medical exam component, focusing on general health, cognition, vision, and hearing testing, although the evaluation process does vary from program to program. Performance testing is part of the evaluation in 6 of the health systems and is done by peer assessment in 4, and only done by dexterity testing in 2. In the peer review assessment, two policies address the technical and procedural competencies required by surgeons to safely and effectively perform surgery. The evaluation of these technical competencies is subjective in nature, where candidates are rated on scale from "significant concern" to "outstanding" clinical competence. Observed performance or behavior that influenced the peer assessment must be commented if labeled "significant concern" or "minor concern". The results of the testing could be used to modify the physician's privileges in 7 of the 9 health systems identified.

Competency assessments in the workplace

Licensing bodies and certification boards in the United States and Canada use CME and MOC as assessment methods to ensure continued clinical competency in the surgical workplace of board-certified surgeons (Table 3). However, these competency evaluations only address knowledge and do not take into account surgical skills, and to some degree judgment. State and provincial licensing bodies can initiate a competency evaluation by independent evaluator if a surgeon has been identified to the licensing body as performing below the accepted level of competency. Within the hospital setting, the surgeon-in-chief is primarily responsible to the community for the safety of the operating room and the competence of surgeons on the staff.

Several tools using surgical simulation or direct observation are currently being used on practicing surgeons to evaluate performance and technical skills needed for a surgical specialist (Table 3). Six of these tools reliably and accurately detect different level of technical skills among study participants, consisting of surgical trainees, fellows, and staff. All of these methods were validated for surgical trainees. Objective Structured Assessment of Technical Skills (OSATS) is the only method capable of distinguishing between surgeons of different skill level and showing a relationship

Table 2 Late career practitioner policies adopted at health institutions

Program	Objectives	Candidates	Medical exam	Performance testing	Modification of privileges
Stanford Health Care[16,17]	To ensure high quality care for patients and protect them harm and identify health concerns of practitioners	74.5 years old and every 2 yr thereafter	Comprehensive history and physical examination including vision, hearing, neurological, and cognitive testing	Peer assessment by hospital staff of technical and procedural competencies, relative to Stanford expectations	Yes, if non-compliant or unsafe practice patterns
Aging Surgeon Program at Sinai Hospital, Baltimore, MD[43]	Designed to protect patients from unsafe surgeons and guard surgeons from arbitrary or unreliable methods of assessing competence or cognitive capacity. The program can identify potentially treatable or reversible disorders that, if properly treated, could restore or improve functional capacity	No mandatory age. Requested from surgeons, hospitals or licensing bodies of all surgical sub-specialties	Evaluation of general health, vision, hearing, neurocognition, visual-spatial and fine motor capability	None	No
Hartford Health Care[44]	To ensure patient safety and high-quality medical care	70 years old and above, and annually thereafter	Annual physical exam, vision, neurological testing and neuropsychological screening	OPPE. FPPE if needed, to identify patterns that may negatively impact quality and safety of care	Yes, discussion with department Chief ± Credentials Committee if deemed unable to safely exercise privileges
YNHH[21,45]	To protect patients from harm and safeguard fair physician assessment	70 years old and above	Ophthalmologic exam and 16 test neuropsychologic screening battery	None	Yes, MSRC suggestions based on screening results
Legacy Health, OR[46]	To assess physicians to ensure patient safety and physician wellness	70 years old and above, and every 2 yr thereafter	Physical capacity by occupational therapy and neuropsychological testing	Peer review assessment	Yes, determined by Credentials Committee, if health problems interfere with safe practice
Driscoll's Children's Hospital, Corpus Christi, TX[17]	To assure that patient safety and quality are adequately supported by carefully assessing the capabilities, competencies and health status of each practitioner	70 years old and above	Comprehensive examination addressing physical and mental capacity by a physician	Peer review assessment may be required. Must meet technical and procedural competencies	Yes, determined by Credentials committee, if practice unsafe or incompetent
University of Virginia Health System[17]	To assess each physician's capacity to perform requested privileges	First assessment at age 70. Annual assessment after 75 years of age	Comprehensive examination addressing physical and mental capacity under the Physician Wellness Program	None	Yes, as determined by Department Chair
UC San Diego LCHS[47,48]	To detect any physical or mental health problems that may affect a physician's ability to practice	70 years old and above. At request of hospital or medical group	History and physical exam. Cognitive and mental health screen	Dexterity tests for proceduralists/surgeons	No
Tahoe Forest Health System, CA[49]	To fairly and accurately evaluate physician performance and capabilities	70 years old and above. Required to partake in LCHS	See LCHS	See LCHS	Yes, after consultation with department Chair if adjustment is required

OPPE: Ongoing Professional Practice Evaluation; FPPE: Focused Professional Practice Evaluation; YNHH: Yale New Haven Hospital; MSRC: Medical Staff Review Committee; LCHS: Late Career Health Screening for Physicians and Healthcare Professionals.

between skill level and post-operative outcomes.

Surgical procedures and/or skills are evaluated by an expert, or non-medically trained reviewers with regards to Crowd-Sourced Assessment of Technical Skills (C-SATS), using a paper-based tool in six of the object assessments, blinded to the post-graduate year of the participant. The objective assessments were designed for common surgical procedures extending over multiple specialties, including laparoscopic cholecys-tectomy, open reduction and internal fixation (hip, wrist, or ankle), arthroplasty, and robotic prostatectomy. Global Operative Assessment of Laparoscopic Skills (GOALS) and Global Evaluative Assessment of Robotic Skills (GEARS), however, target laparoscopic and robotic surgery only. The last tool, Direct Objective

Table 3 Existing methods for determining surgical competency

Method	Basic structure	Assessment	Procedure examples	Validated[1] for	
				Practicing surgeons	Surgical trainees
Licensing bodies assessments					
State Medical Boards[50-52]	Mandatory to practice. Required to demonstrate competency through CME. However, states individually may evaluate professional conduct when a physician fails to provide appropriate quality of care	Must regularly participate in CME activities and may require board certification. May have competency evaluation by independent evaluator or approved assessment program if signs of dyscompetence	-	Unclear	-
ABMS[18,19]	Voluntary certification to show knowledge of standards of practice. Rigorous process of evaluation every 10 yr with MOC	MOC consists of 4-part assessment: Licensure/professional standing, participation in CME programs, cognitive expertise through examination, and documentation of quality of care and/or audits or peer review	-	Unclear	-
Provincial Licensing Bodies in Canada[53-55]	Mandatory to practice. Required to demonstrate competency through CME. Provincial licencing bodies identify those with deficiencies in competence, requiring peer review	Must regularly participate in CME activities. If evidence of dyscompetence, rigorous individualized assessment of the surgeon's practice is performed, with emphasis on quality of care	-	Unclear	-
Fellows of the RCPSC[56,57]	Voluntary certification to show commitment to competent practice. Evaluation and successful completion of MOC program every 5 yr	Must participate in CPD activities. MOC based on 3 section framework: Group learning, self-learning, and assessment	-	Unclear	-
Non-licensing bodies assessments					
OSATS[58-61]	Multi-station and timed with bench and live model simulations or surgical procedures. Peer evaluated with rating scale	Checklist and global rating scale by expert examiner to evaluate technical skill. Does not assess decision making or concrete surgical aspects	Laparoscopic Gastric Bypass Saphenofemoral dissection. Meniscectomy transtibial or anteromedial femoral tunnel	Yes	Yes
C-SATS[26,31]	Video recorded surgical performance and evaluated with validated with rating scale	Crowds of anonymous and independent reviewers, including those nonmedically trained, evaluate surgical skill with validated performance tools such as OSATS	Urinary bladder closure. Robotic surgery skills	No	Yes
O-SCORE[27,62]	Surgical procedure peer evaluated with rating scale	Surgical experts rate performance with 9 item tool and scaling system to assess competence to perform procedure independently	Open reduction internal fixation of hip, wrist, or ankle. Arthroplasty (total hip or hemi). Knee arthroscopy	No	Yes
GOALS[63,64]	Laparoscopic procedure peer evaluated with rating scale	Surgical experts evaluate performance with 5-point rating scale of 5 items unique to laparoscopy	Laparoscopic cholecystectomy	No	Yes
GEARS[65,66]	Robotic procedures peer evaluated with rating scale	Surgical experts evaluate performance with 5-point rating scale of 6 items unique to robotic surgery	Inanimate simulators–continuous suturing. Prostatectomy	No	Yes
Direct Objective Metric Measures[67,68]	Skill/surgical procedure measured with concrete aspects	Measurement of stiffness and failure load for each repair construct, with comparison to expected rehabilitation loads	Tibial plafond fracture reduction. Distal radius fracture reduction	No	Yes

[1]To note: Methods to determine surgical competency are deemed valid for (1) Experienced surgeons; or (2) Residents/trainees if the assessment (continuing medical education, maintenance of certification or rated technical skill) correlated with experience level and/or with patient outcomes. Validity was shown for specific procedures within specific subspecialties. For example, experienced bariatric surgeons who had higher rated technical skill in laparoscopic gastric bypass surgery had patients with fewer post-op complications[46]. Generalized validity has yet to be shown in literature with regards to the technical skill assessments, although validity was typically demonstrated across several procedures. ABMS: American Board of Medical Specialties;

CME: Continuing medical education; MOC: Maintenance of certification; RCPSC: Royal College of Physicians and Surgeons of Canada; CPD: Continuing professional development; OSATS: Objective structured assessment of technical skill; C-SATS: Crowdsourced assessment of technical skills; O-SCORE: Ottawa Surgical Competency Operative Room Evaluation; GOALS: Global operative assessment of laparoscopic skills; GEAR: Global evaluative assessment of robotic skills.

Metric Measures, uses measurable metrics to determine skill level instead of technique. Direct Objective Metric Measures investigate the stiffness and failure load of the final surgical product, which are critical within the orthopaedic field.

DISCUSSION

For almost all of history, people worked until they died. Retirement is a recent phenomenon, starting during the Great Depression when governments, unions, and employers, desperate to make room in the workforce for young workers institutionalized retirement programs as we know them today, complete with social security and pension plans. Initially, the designated retirement age of 65 was longer than the life expectancy, but as life expectancy has increased, retirement age in certain professions has become more arbitrary. Surgeons may continue to work longer than other professionals because of their satisfaction and gratification in treating patients, because their work connects the surgeon to an identity or for financial reasons. Surgeon’s retirement age remains a contentious issue and presently there is no mandatory retirement age for surgeons. Furthermore, we could not find any universal, well-established and accepted policies of testing for competency of aging surgeons.

Although a review of 65 studies of physicians’ retirement planning found that most physicians retire between ages 60 and 69 years, some surgeons delay retirement because of financial insecurity, lack of other interests or fear of change in their personal lives and identity[20]. Despite the well-recognized decline of cognitive and physical skills with ageing, most surgeons only require verification of their CME to maintain their medical license to practice, in the absence of skill-based simulations that regulate non-medical professionals. Airline pilots, air traffic controllers, firefighters, and United States State Judges were found to have thorough medical examinations and skill assessments during their practice. Regardless of inherent ability, they are further subjected to mandatory retirement ages. Although the United States Age Discrimination and Employment Act of 1967 protects individuals at or above the age of 40 from mandatory retirement ages, employers have established a legitimate age-based criterion referred to as a bona fide occupational qualification (BFOQ), allowing them to justify an age-based BFOQ for certain professions.

Despite age being a variable process, the potential association within the surgical profession between increasing age and poorer operative outcomes has been reported in some studies[9-12]. The mandatory late career practitioner policies identified in this study begin to address the competency of the surgical workforce, through cognitive and physical testing. Performance testing consisted of peer-review assessment and varied across the different health institutions. In the absence of standardized technical skill assessments and continued legal challenges[21], age may not be the most reliable and objective performance indicator.

Surgeons, like other medical specialties, need to regularly engage in activities that keep them up to date with standards of care. However, the requirements to be certified or licensed are highly dependent on the standards developed by individual states, provinces or specialty boards. Furthermore, the validity of CME and MOC, defined as the ability to distinguish expertise level and effects on patient outcomes, was noted as unclear based on available literature. CME, such as didactic educational meetings, were shown to have only a small effect on clinical practice and patient outcomes[22,23]. Completion of MOC is not associated with differences in complication rates in specific surgical subspecialties[24]. In fact, surveyed surgeons were in favor of improving MOC with additional testing such as cognitive assessments or review of cases for older surgeons, in place of a mandatory retirement age[25]. Meeting CME or MOC requirements alone does not guarantee a successful surgical practice, despite being used to certify surgeon competency.

Similar to the testing of pilots and air traffic controllers, there are surgical simulators designed to provide an objective assessment of surgical technical skills. Although these simulators have been used primarily for surgical residents to gauge their level of training, surgical simulators can equally be used to evaluate practicing surgeons by their peers or recognized experts[26,27]. These simulators may then be used to assess surgical competency among, not only older surgeons, but all surgeons as part of their medical education, showing who may require remediation or retirement. However, one of the most significant limitations in the use of simulation for assessing competence for aging surgeons–namely the ability to evaluate the most important skill that dictates surgical expertise and competence: Intra-operative cognitive skills. To date, very few if any surgical simulations have demonstrated the ability to assess advanced mental processes such as decision-making and judgment; and pattern recognition. These cognitive behaviors (or "thinking skills") are some of the most important aptitudes that dictate performance in the operating room and better methodologies are required to measure them[28]. In addition, the use of simulators would need to be specialty specific and the specialty societies have not yet built these programs.

While this study demonstrated that current competency assessment methods for older surgeons require improvement, the study was limited by various factors. This study is a scoping review, thereby providing an overview of an important topic, without describing every possible assessment tool. Information regarding non-medical specialties was constrained to predefined professions, weakening the comparative analysis between these professions and surgeons. Other non-medical professions were not investigated, although the ones presented are commonly known. The number of late practitioner policies identified was also small, as they needed to be accessible online. It is clear that other policies exist, some of which have been referenced to online, such as Sharp Rees-Stealy Medical Group, Intermountain Healthcare in Utah, Scripps Health network in San Diego, Arkansas Children's Hospital, Cooper University Hospital, University of Pittsburgh Medical Center, and Virtua Health[29,30]. However, their policies are not explicitly described so that it is unclear whether or not these policies address older surgeon competence in a similar manner to the policies discussed in this study, or in a manner separate from cognitive testing or peer-assessment. As well, there are likely other late practitioner policies that exist but are not present online. In addition, the non-licensing body surgical simulators have been studied across different procedures within different specialties, but the generalizability remains in question. For example, Crowd Sourced Assessment of Technical skills (C-SAT) was shown to be valid for robotic skills amongst urology residents but whether it is valid in orthopaedics or other specialties is not known[26,31]. And given that these surgical simulators have largely been validated for distinguishing skill among surgical residents, more studies need to evaluate the validity and reliability of these simulators for staff surgeons before even considering implementation. In addition, even when there is a valid technique for objective assessment of competence in the execution of particular operations by surgeons, such as the assessment of intraoperative videos, there has been low utilization due to its labor-intensive nature involving human factors (cognitive engineering) expertise[32].

CONCLUSION

Surgery is a profession that requires good surgical judgment, as well as manual dexterity and physical skills for performing an operation. Age alone is not an indication of surgical competence, so testing of these attributes is necessary to ensure that the ageing surgeon remains competent. This requires regular periodic review of the surgeon's outcomes and skills to ensure that the ageing surgeon has the competency to meet the standards of the profession. The strategy of using skill-based simulations in evaluating non-medical professionals can be similarly used as part of the assessment of the aging surgeons' surgical competency. While more studies investigating the validity of these simulators is needed, future implementation of these simulators may ensure all aging surgeons maintain an appropriate professional standard for patient safety. A surgeon should not be forced to hang up his/her surgical cap at a predetermined age, but should be able to practice for as long as his/her surgical skills are objectively maintained at the appropriate level of competency. For those aging surgeons with a diminishing skillset, there other potential options to integrate these surgeons into important aspects of surgical care such as assisting younger surgeons for more complex cases, teaching and training the next generation of surgeons, coaching surgeons in practice, being involved in quality-improvement and leadership roles.

ARTICLE HIGHLIGHTS

Research background

The aging surgeon has remained a contentious patient safety issue, as the average age of surgeons continues to rise.

Research motivation

When should an older surgeon stop operating? This becomes an important issue when we consider that the surgical profession is highly dependent on memory, sensory acuity, clinical decisiveness, technical skills and physical stamina; skills and abilities that may decrease with age.

Research objectives

The aim of this scoping review study was to investigate strategies used to determine competency in the industrial workplace that could be transferrable in the assessment of aging surgeons and to identify existing competency.

Research methods

Scoping review.

Research results

Surgeon's retirement age remains a contentious issue and presently there is no mandatory retirement age for surgeons. Furthermore, we could not find any universal, well-established and accepted policies of testing for competency of aging surgeons.

Research conclusions

A surgeon should not be forced to hang up his/her surgical cap at a predetermined age, but should be able to practice for as long as his/her surgical skills are objectively maintained at the appropriate level of competency.

Research perspectives

More studies need to evaluate the validity and reliability of these simulators for staff surgeons before even considering implementation.

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CASE REPORT

Salmonella infection after anterior cruciate ligament reconstruction: A case report

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Abstract

BACKGROUND

Infections after anterior cruciate ligament reconstruction (ACLR) are rare. No cases of *Salmonella* infection have been described to our knowledge.

CASE SUMMARY

We describe a rare case of *Salmonella* infection in a 23-year-old patient following an ACLR. The patient presented with subacute septic arthritis, 26 d after a hamstring autograft ACLR. The pathogen, *Salmonella enterica typhimurium* was isolated by bacteriological sampling of the first arthroscopic lavage. Two arthroscopic lavages were required, with intravenous antibiotic therapy for two weeks with cefotaxime and ciprofloxacin, followed by oral antibiotics with amoxicillin and ciprofloxacin for a total duration of three months. This approach treated the infection but two years after the septic arthritis, faced with ongoing knee instability due to graft damage, a revision ACLR with a bone-tendon-bone graft was performed. At the last follow-up, full range of knee motion had been achieved and sports activities resumed.

CONCLUSION

Infection after ACLR is rare and requires an early diagnosis and management in order to treat the infection and prevent arthritis-related joint cartilage destruction and damage to the graft.

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Core Tip: Infection after anterior cruciate ligament reconstruction (ACLR) is uncommon, with staphylococci found in more than 90% of cases. We present herein, an exceptional case of *Salmonella* infection after ACLR. This case highlights the importance of early diagnosis and management: arthroscopic washing for acute infections or arthrotomy for late infections and appropriate antibiotic therapy. The purpose of the surgical treatment is to prevent arthritis-related joint cartilage destruction and to protect the graft.

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INTRODUCTION

Septic arthritis after anterior cruciate ligament (ACL) reconstruction (ACLR) is a rare but severe complication, with an incidence between 0.3% and 1.7%[1-3]. The main responsible pathogens are *Staphylococci* (coagulase-negative and *S. aureus*) and *Streptococci*[2,4-6].

Salmonella spp are Gram-negative bacilli, belonging to the enterobacteriaceae family and responsible for digestive infections. Contamination is mainly caused by the consumption of raw or undercooked food (meat, eggs, and dairy products), or food contaminated by the excreta of carrier animals (more rarely by direct animal contact). After a short incubation period, these pathogens are responsible for an inflammatory intestinal syndrome with mucoid bloody diarrhea. Extra-intestinal complications, including osteo-articular complications, are rare (< 1%) and associated with haematogenous spread[7]. Typhoid fever is caused by *Salmonella spp* and osteo-articular complications occur in less than 1% of cases, arising in one of three possible ways: haematogenous spread, contiguous source, or as a result of vascular insufficiency[8]. The risk factors include sickle cell anaemia, diabetes, systemic lupus erythematosus, lymphoma, liver diseases, previous surgery or trauma, those at extremes of age, and steroid use[9].

We report herein a rare case of *Salmonella enterica typhimurium* following ACLR. To our knowledge, this is the first case of septic knee arthritis after ACLR due to *Salmonella spp*.

CASE PRESENTATION

Chief complaints

Twenty-six days after an ACLR, a 23-year-old man showed a deterioration in his general state (asthenia, fever and chills) and local signs of an early knee septic arthritis: pain, heat, redness, and edema.

History of present illness

The patient reported an episode of abdominal pain associated with mucoid bloody diarrhea 10 d before the onset of the arthritis symptoms, which quickly resolved within 48 h. Further questioning on risk factors for *Salmonella spp* revealed the patient had eaten an egg-based picnic 24 h before these symptoms appeared.

History of past illness

This patient was suffering from chronic instability in his right knee, following a soccer injury. An isolated ACL injury was reported on magnetic resonance imaging (MRI).

Three months after the injury, an ACLR was performed, using a hamstring autograft (semi-tendinosus and gracilis). The procedure was performed under general anesthesia with a tourniquet at the proximal thigh for duration of 40 min. An outside-in drilling technique was used for the femoral tunnel. Femoral and tibial fixation was with interference screws.

The patient followed a standardized post-operative rehabilitation protocol aimed at controlled restoration of range of motion, muscle strength and proprioception. He was discharged the same day full weight bearing assisted with crutches. At 15 d after surgery, a routine consultation was performed to verify the absence of pain, hematoma, wound inflammation and/or serous or purulent discharge.

Personal and family history

The patient had a free previous medical history.

Physical examination

A collection in the external femoral approach site was confirmed.

Laboratory examinations

A biological inflammatory syndrome was found with an initially raised C-reactive protein (CRP) of 51 mg/L increasing to 130 mg/L over the first 24 h (Figure 1), alongside a white blood cell count increase from 11000/mm^3 to 13300/mm^3 during the same period.

The joint fluid aspiration performed in the emergency room showed neutrophils at direct examination and was followed by administration of intravenous antibiotic therapy – oxacillin 2 g every 8 h and gentamycin – 270 mg/d.

Imaging examinations

A knee ultrasound examination reported an intra-articular effusion. X-rays showed no fracture.

FINAL DIAGNOSIS

Salmonella enterica typhimurium arthritis following an ACLR.

TREATMENT

An urgent arthroscopic joint lavage was performed the same day. The joint fluid was serous, not purulent. with few false membranes but without a clear inflammation of the synovial tissue. A surgical approach centered on the scar for the femoral tunnel, was also performed and revealed a separate collection apparently extra-articular. Multiple samples were taken for bacteriological analysis. Intravenous antibiotic therapy with oxacillin at a dose of 2 g every 8 h and gentamycin at a dose of 270 mg per day was continued pending bacteriological results.

The stool and blood cultures returned negative. Samples of joint fluid aspiration and arthroscopic lavage both grew *Salmonella typhimurium* on aerobic cultures.

This result was also confirmed by polymerase chain reaction (PCR) DNA 16S. Antibiotic therapy was modified to cefotaxime at a dose of 3 g every 6 h and ciprofloxacin at a dose of 400 mg every 8 h.

The clinical and biological evolution was not favorable, on the 6th post-operative day, a knee effusion and a collection in the external femoral approach was seen, as well as a biological inflammatory syndrome, with a CRP increase up to 450 mg/L (Figure 1). Therefore, a second arthroscopic lavage was performed. The external femoral approach was again opened and now revealed a purulent collection, communicating with the joint. Arthroscopy showed purulent joint effusion with false membranes and an inflammatory synovial tissue (Figure 2).

Multiple bacteriological samples were taken, followed by lavage. The samples returned sterile and 16S DNA PCR was negative.

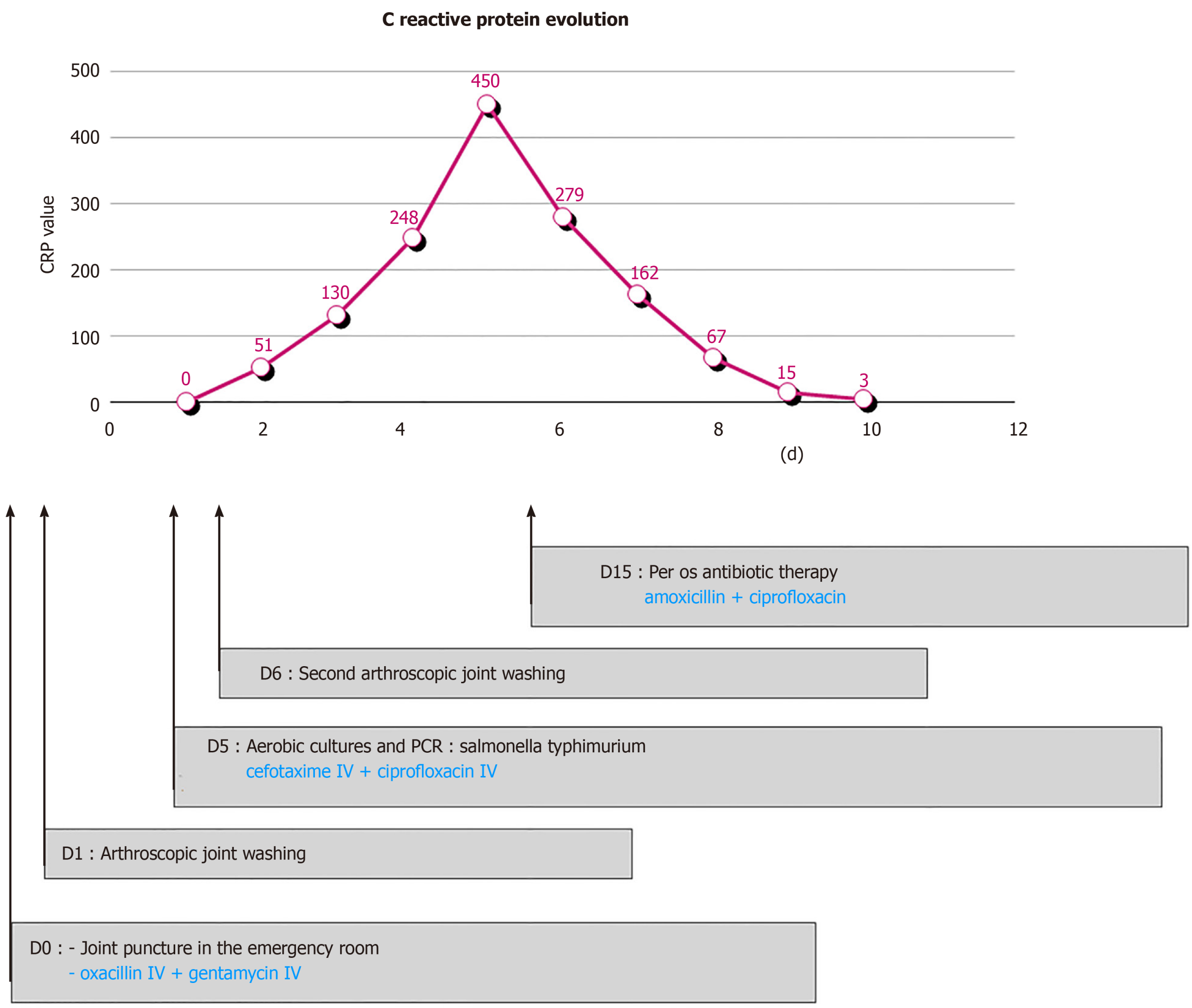

Figure 1 C reactive protein evolution and therapeutic management. CRP: C-reactive protein; PCR: Polymerase chain reaction; IV: Intra venous.

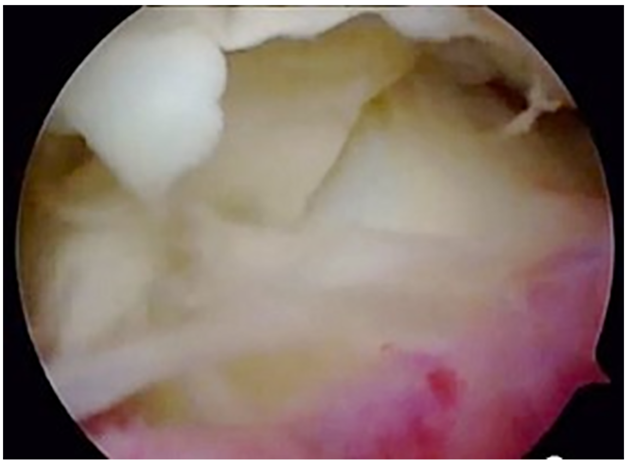

Figure 2 Second arthroscopy, showing false membranes and synovitis.

OUTCOME AND FOLLOW-UP

Over the subsequent days, a decrease in local inflammation as well as a decrease in biological inflammatory syndrome was seen, with a normalized CRP (< 5 mg/L) at 1 mo (Figure 1).

A total of 3 wk of hospitalisation was required, with oral antibiotic therapy started after 15 d of intravenous treatment with amoxicillin at a dose of 1 g, 3 times daily and ciprofloxacin at a dose of 500 mg, twice daily for a total of 3 mo of antibiotic therapy.

Two years after the septic episode, the infection was considered cured but a persistent knee instability (with positive Lachmann-Trillat and jerk-tests) persisted. Furthermore, MRI showed a partial rupture of the graft. In order to meet the patient's desire to resume a pivotal sports activity, a revision ACLR was scheduled, using a bone-tendon-bone graft reconstruction combined with a Lemaire procedure. Intra-operatively, a distended and non-functional ACL graft was found. Prophylactic antibiotic therapy with amoxicillin at a dose of 150 mg/kg/d in 4 injections was initiated pending the microbiology results of tissue samples. Antibiotic therapy was stopped on day 5, due to the sterility of the bacteriological samples.

Final follow-up at three years after the surgical revision revealed a full range of stable knee motion, with function similar to the contralateral knee, allowing pivoting sports activities (soccer).

DISCUSSION

We report an uncommon case of *Salmonella enterica typhimurium* arthritis in a young patient, following an ACLR.

Infections after ACLR are rare, and no cases of *Salmonella* infection have been described to our knowledge. The main responsible pathogens are *Staphylococci* (coagulase-negative and *S. aureus*) and *Streptococci*[2,4-6]. This case occurred early after ACLR, however given the history, haematogenous spread from the primary bowel infection is presumed.

Salmonella non typhi have been rarely reported as agents of arthritis. *Salmonella* is a Gram-negative *Bacillus Enterobacteriaceae* responsible mainly for digestive infections. The prevalence of joint infections with *Salmonella* is only 1%[7]. It mainly affects the native hip in children[10]. Some cases of *Salmonella* arthritis after total hip or knee arthroplasty have been described in the literature (Table 1).

Risk factors for bacterial blood-borne knee infections (old age, diabetes, polyarthritis and other immunodeficiency diseases as well as intravenous drug abuse) were not found in this patient, nor were other described risk factors such as concomitant meniscus resection or a history of surgery on the same knee[11].

For ACLR, hamstrings autograft has been reported to be a risk factor for surgical site infection compared to bone-tendon-bone graft reconstruction[5].

Septic arthritis is an orthopedic emergency. The gold standard of treatment is joint debridement and antibiotic therapy according to the culture results. Smith *et al* reported that enzymatic destruction begins by the eighth hour after the inoculation. By the 48th hour, 40% of the glycosaminoglycan is lost, and collagen breakdown occurs in a period of few days in septic arthritis[12]. Several studies have shown that the duration between the beginning of symptoms and surgical intervention is the most important prognostic factor for septic arthritis[13,14]. Early diagnosis and management are essential to minimize the risk of graft failure and osteo-articular lesions, which cause stiffness and chronic pain. It is recommended to hospitalise the patient and give the appropriate treatment within 24 h[1,15-17]. The reference treatment is as follows (Figure 3) : first surgical treatment by knee debridement and lavage with attempts to protect the graft in most cases and then medical treatment by intravenous antibiotic therapy with penicillin (cloxacillin), initially targets the most frequently encountered pathogens (*Staphylococcus aureus*, *enterobacteria* and *streptococci*).

Blind joint fluid aspiration is not described in the optimal management of infection after ACLR and antibiotic therapy initiated before the first arthroscopic lavage in our patient could have negated the results of bacteriological samples, resulting in a delay in optimal management and therefore decreasing the chances of saving the graft[16]. For acute (less than 2 wk postoperatively) and subacute (between 2 and 8 wk) infections, arthroscopic debridement and lavage can be proposed, while for chronic infections (after 8 wk postoperatively) an open lavage *via* an arthrotomy has been recommended. Additional lavage may be necessary if the initial treatment fails. The modalities of management, in this case, are ambiguous: some would perform a second lavage

Table 1 Literature review on *Salmonella* infection after total hip or knee arthroplasty

Ref.	Prosthetic joint	Prosthesis age at time of infection	Symptoms	Microbiology	Surgical treatment	Antibiotic therapy	Failed treatment
Chong and Sporer[20], 2005	THA	8 mo	Purulent flow	*Salmonella choleraesuis*	Two-stage revision	IV vancomycin oral ciprofloxacin 6 wk	No
Gupta *et al*[21], 2014	TKA	3 yr	Deep joint pain, discomfort for 4 mo	*Salmonella enterica serovar Enteritidis*	Removal, debridement and arthrodesis after aspiration failed and oral TMP-SMX 12 wk	Oral TMP-SMX 8 wk	No
Gupta *et al*[21], 2014	THA	7 yr	Pain	*Salmonella enterica serovar Enteritidis*	Removal, debridement and arthrodesis after debridement failed and oral amoxicillin 10 mo	IV ampicillin 4 wk	No
Gupta *et al*[21], 2014	THA	5 mo	Fever, pain, joint swelling	*Salmonella enterica serovar Choleraesuis*	Two-stage revision after aspiration failed and oral ampicillin 8 wk	Oral ampicillin4 wk	No
Gupta *et al*[21], 2014	THA	4 yr	Fever, pain, swelling	*Salmonella enterica serovar Enteritidis*	Two-stage revision	Oral ciprofloxacin8 wk	No
Gupta *et al*[21], 2014	THA	5 mo	Fever, pain	*Salmonella enterica serovar Enteritidis*	Two-stage revision	IV ceftriaxone 6 wk	No
Gupta *et al*[21], 2014	THA	9 yr	Pain	*Salmonella bongori*	Two-stage revision after aspiration failed and oral ciprofloxacin 8 wk	IV ceftriaxone 6 wk	No
Toth *et al*[10], 2010	THA	2 yr	Pain	*Salmonella enteridis*	Two-stage revision	Oral ciprofloxacin 6 wk	No
Toth *et al*[10], 2010	THA	7 yr	ARDS caused by sepsis and increased uptake aroud the THA (autolog leukocyte scintigraphy)	*Salmonella cholerae-suis*	Two-stage revision	Oral ciprofloxacin 6 wk	No
Sebastian *et al*[22], 2017	TKA	4 yr	Pain, swelling, scare discharge, limitation of range of motion	*Salmonella typhimurium*	Two-stage revision	Oral ciprofloxacin 6 wk	No
Carlile *et al*[23], 2010	TKA	5 yr	Pain, swelling, fluctuant swelling, night sweats and shivering	*Salmonella enterica choleraesuis*	Two-stage revision	IV cefotaxim 7 d. Oral ciprofloxacin 3 wk	No
Jeroense *et al*[24], 2014	THA	5 d	Fever	Group E *Salmonella*	One-stage revision after lavage failed and ciprofloxacin 4 wk	Oral ciprofloxacine 5 mo	No
Jeroense *et al*[24], 2014	THA	13 years	Pain, abscess at the ultrasound	*Salmonella enteritidis*	One-stage revision	Oral ciprofloxacine 3 mo	No

IV: Intra venous; THA: Total hip arthroplasty; TKA: Total knee arthroplasty; TMP-SMX: Trimethoprim and sulfamethoxazole.

arthroscopically and others would prefer an arthrotomy[16,18].

The presence of an abscess in the surgical wound, backed by a CRP increase despite the surgical and antibiotic treatment, justified a second lavage in order to reduce the bacterial inoculum. In this patient case, the subacute infection justified the use of an arthroscopic approach instead of an arthrotomy. An open arthrotomy could also have been performed if arthroscopic treatment had failed. In this case, iterative arthroscopic management has been successful to control the infection. Antibiotic therapy is adapted after analysis of antibiotic sensitivity, and continued until the clinical-biological evolution is satisfactory, an antibiotic treatment of at least 6 wk is recommended[19].

The initial antibiotic therapy used in this patient was appropriate because it is effective for the most frequent pathogens (*i.e.*, *staphylococci*). It was adapted after antibiotic sensitivities. *Salmonella* is sensitive to third generation cephalosporins and fluoroquinolones, which were administered to our patient once the bacteriological results were obtained[7,11].

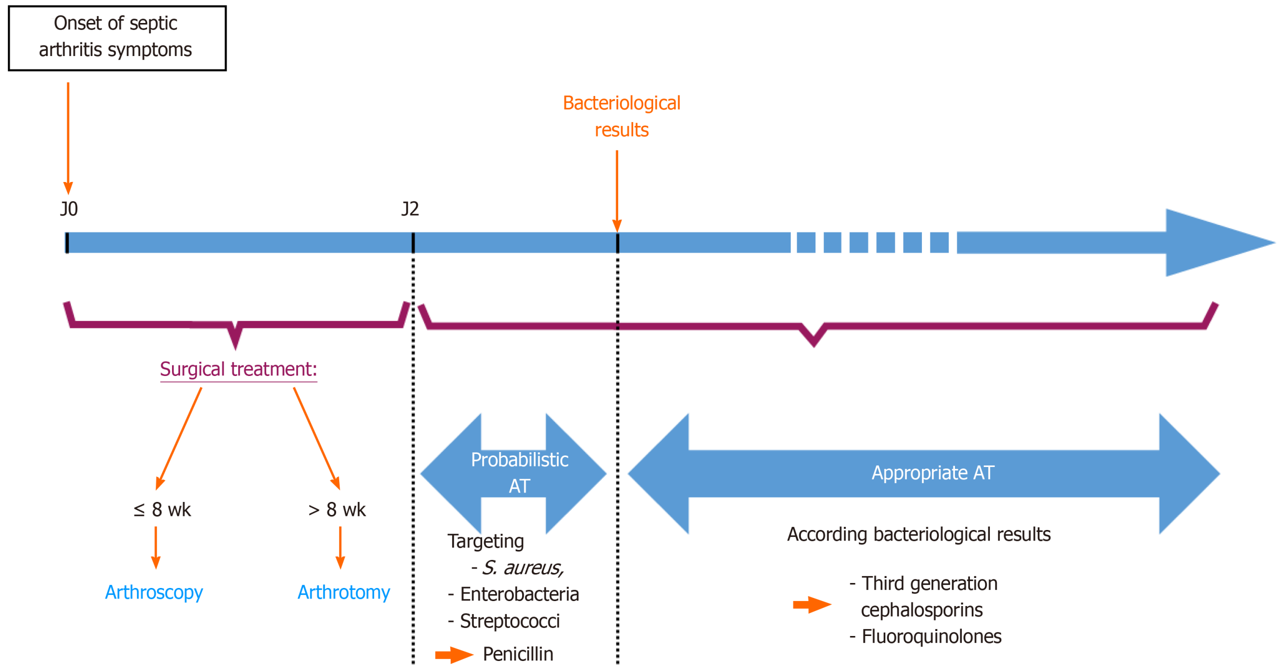

Figure 3 Therapeutic management schema. AT: Antibiotic treatment.

Graft failures are rare in early management of infection[16]. For this patient, the causes may have been as follows: The 24 h delay in treatment due to the aspiration, the absence of graft debridement, the pathogen (since no cases of *Salmonella* septic arthritis after ACLR are described), but likely primarily due to the two successive surgical procedures that could have compromised the integration of the graft.

CONCLUSION

Infection after ACLR is uncommon, with staphylococci found in more than 90% of cases. This case highlights the importance of early diagnosis and management: arthroscopic lavage for acute infections or arthrotomy for late infections and appropriate antibiotic therapy. Like any septic joint, early aggressive surgical treatment is required, also aiming to reduce the risk of arthritis-related joint cartilage destruction and damage to the graft.

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