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Changes in joint lubrication with the degree of meniscectomy and osteochondral junction integrity

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ABSTRACT

This study focuses on the relationship between meniscectomy and osteochondral junction health, and their integrity on cartilage lubrication. Using a previously published multi-component joint computational model, we explored the impact of increasing degree of meniscectomy and osteochondral flow conductivity on joint lubrication. Results suggest a greater effect of meniscectomy on joint lubrication when the osteochondral junction is healthy. However, the impact is less pronounced when the osteochondral junction is already diseased due to compromised lubrication capability. This research provides a first-time quantitative analysis of this interaction, which highlights the importance of adequately evaluating the osteochondral junction's condition before meniscectomy surgery. It also suggests that reducing post-surgery activity level may be beneficial for patients with diseased junctions undergoing meniscectomy.

1. Introduction

The meniscus is a C-shaped fibrocartilage in the knee joint sitting between the femur and tibia [1], which is held in place by the meniscofemoral ligaments [2,3]. It plays a crucial role in joint function [2,4,5], particularly by distributing load and aiding joint stability [6,7]. Recent advancements in understanding the biomechanics of the meniscus have emerged from cadaveric experiments and finite element modelling (FEM) [8–10]. However here the focus is on the meniscus' role in joint lubrication, particular following injury associated with joint disease.

Meniscus injuries are prevalent, particularly in sports-related activities, which can have significant functional consequences for these patients [11,12]. Each year, there are more than one million meniscal surgeries performed worldwide [13–15], with meniscus injuries being especially common among the elderly [12]. The high prevalence of meniscus injuries is concerning because they represent a significant risk factor for the development of osteoarthritis [12,16,17].

The meniscus is essential for normal joint function, protecting the joint by distributing joint loads over a larger contact area. This reduces both average and peak contact stress and so decreases cartilage tissue deformation [6,7]. This protective function of meniscus decreases the likelihood of tissue damage, cell death due to large deformation, excessive surface wear leading to early onset of osteoarthritis (OA) [18]. The decreased contact stress, from a biphasic perspective, leads to a lower transient fluid pressure gradients and longer flow paths within cartilage tissue. This slows fluid drainage and prolongs the duration of fluid load support and mixed-mode lubrication [19].

The meniscus plays an important role in extending the flow path of synovial fluid in the contact gap [3,20], which nourishes the cartilage and reduces the friction and surface wear [2,19]. The synovial fluid is a viscous and non-Newtonian fluid present in the joint cavities with exceptional lubrication properties due to its unique composition with hyaluronic acid and lubricin [21–23]. As a rough estimation, it reported that normal synovial fluid is about 50 times more viscous than water in a previous experimental study [24]. Synovial fluid operates under various lubrication regime including hydrodynamic lubrication, boundary lubrication, and mixed-mode lubrication regime (a mix of both hydrodynamic and boundary lubrication mechanism) [19,25]. In hydrodynamic lubrication regime, synovial fluid within the contact gap separates the cartilage surfaces [26]; while in boundary lubrication regime, synovial fluid services as boundary lubricant, reducing direct contact of solid-to-solid matrices [27,28]. However, it is not just the slippery nature of synovial fluid that lubricates the joint surface. It is the

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interactions between the fluid, the contact geometry and surface properties, and the poroelastic mechanical properties of the opposing tissues in the contact that contribute to lubrication. These interactions enhance the longevity of lubrication during extended physical activity. For example, the presence of an intact meniscus extends the flow path length for synovial fluid to egress from the contact gap, thereby increasing the duration of hydrodynamic and mixed-mode lubrication [29]. Any damage to the meniscus, including meniscectomy, is likely to compromise these processes and shorten the duration of hydrodynamic and mixed mode lubrication.

In the joint environment, a deep understanding of tribology becomes crucial especially when the joint undergoes changes such as meniscectomy or due to potential underlying bone diseases as discussed in the following sections. Friction, defined as resistance to relative motion[19], is particularly relevant when considering cartilage surfaces sliding against each other [19]. An increased friction often leads to the formation of wear particles at the contact surface [30,31], and it is generally established that an increased frictional force or applied normal force on the contact surface results in an higher wear rate [31,32]. Lubrication plays a significant role in reducing both friction and wear [19]. In the context of joint lubrication there are primarily two lubrication mechanisms: hydrodynamic lubrication [33] and boundary lubrication. When these two lubrication mechanisms overlap (co-exist) or transition from hydrodynamic to boundary lubrication, it is termed

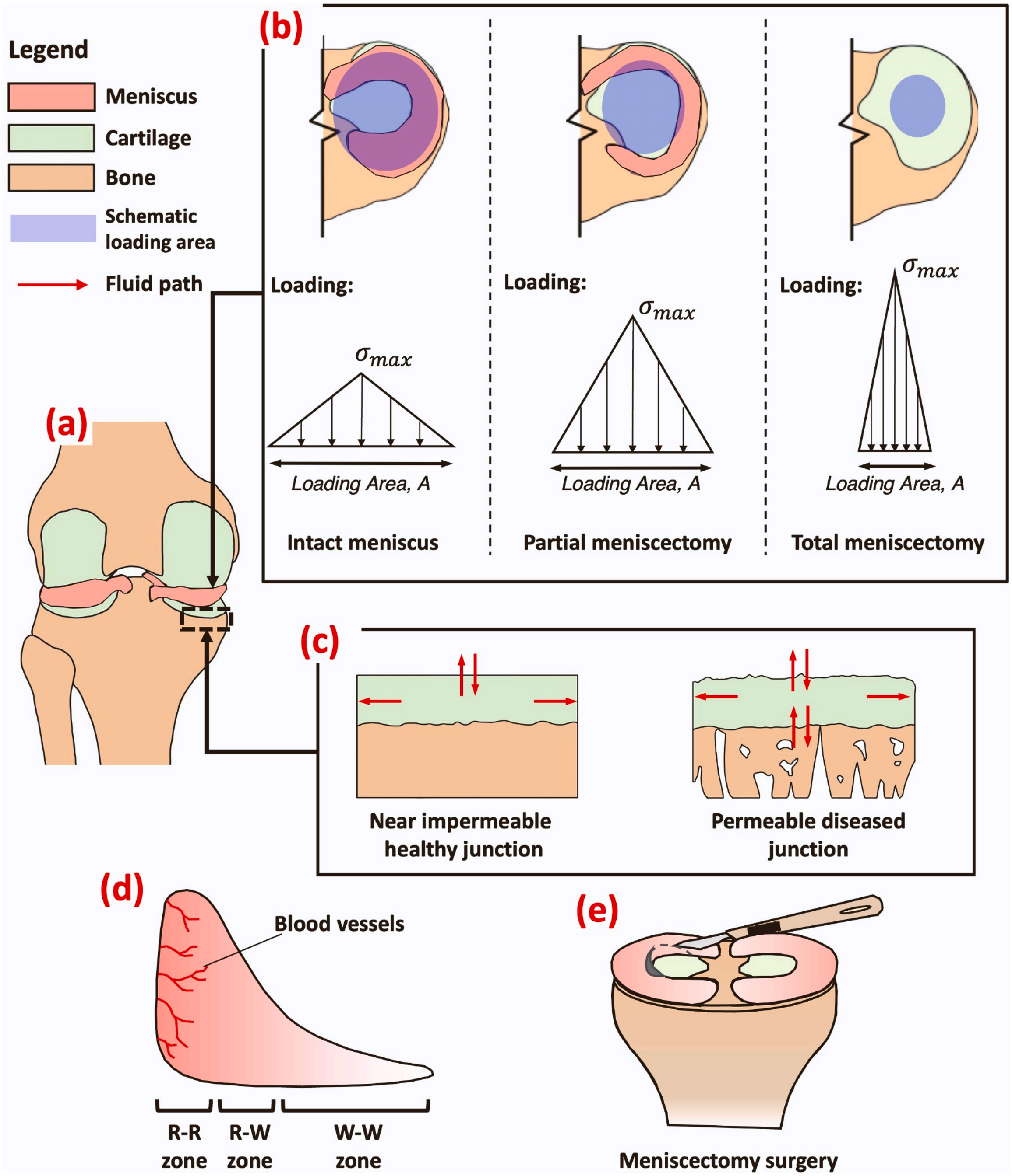

Fig. 1. (a) Schematic diagram of the knee joint; (b) Three scenarios for the extent of meniscectomy, including intact meniscus, partial meniscectomy, and complete meniscectomy along with the schematic conically distributed loading configurations and stress distribution, where σ_{max} is peak contact stress at the loading center, and A is loading area; (c) Two scenarios for permeability at subchondral bone plate region, one for healthy knee joint with no junction leakage, and another one for the permeability under diseased/OA condition; (d) schematic diagram of cross section for meniscus (R: red; W: white); (e) illustration of meniscus removal.

mixed-mode lubrication [19]. It is now widely accepted that under normal conditions, cartilage typically operates within the mixed-mode lubrication regime on daily basis [34–36].

The blood supply to fibro-cartilage within the meniscus is important for its healing capacity [3]. As illustrated in Fig. 1(d), the menisci can be divided into different zones based on their vascularity: the so-named 'outer' (red-red (R-R) zone) with its relatively good blood supply; and the 'intermediate' (red-white (R-W) zone) with a relatively sparse blood supply; and the 'inner' (white-white (W-W) zone) with little to no blood supply [37]. The healing potential of each zone is directly related to the degree of vascularization. Therefore one might expect that traumatic damage to the meniscus in the R-R zone has better healing capacity, while an injured meniscus in the W-W zone is more susceptible to permanent degenerative lesions [37], and so is often surgically debrided (i.e. partial meniscectomy) in an attempt to improve joint mobility in the short term.

Although partial or complete meniscectomy may provide short term improvements in joint function and reduction in discomfort (such as pain relief) following meniscal injuries [38,39], the long-term implication of these procedures is still significant. They may lead to an accelerated onset of OA [40,41]. This is particularly concerning when considering meniscus' role in the knee joint. Beyond biomechanical functions, the meniscus also plays an important role in joint tribology, helping maintain a low-friction environment for cartilage's function. Meniscectomy, by altering or removing the meniscus, it disrupts the joint's intrinsic lubrication mechanisms, potentially leading to elevated friction and wear. Hence, one can expect that the extent of OA acceleration will be influenced by the amount of meniscus removed [6,42]. As a result, patients who have their meniscus removed may need to adopt other measures to protect their knees, such as reducing the level of daily activities [43], and/or even changing occupations. It is essential for surgeons to carefully evaluate the amount of damaged meniscus they need to remove to achieve the best balance between short-term improvements and possible long-term consequences of partial meniscectomy.

The subchondral bone plate (ScBP) is a thin layer of cortical bone located beneath the articular cartilage in the osteochondral junction [44]. The ScBP is usually normal in young adult, and often compromised in aged or diseased joints [45]. In the context of the current study, our concern is specifically with excessively porous, leaky subchondral bone plate, as may occur with aging joints or in a diseased state (such as OA) [46,47]. We refer to excessive fluid movement across the osteochondral junction as 'osteochondral junction leakage'. That is, in this diseased state, there is the ability for significant fluid exchange between the articular cartilage tissue and the subarticular spongiosa bone region due to the abnormally high permeability in the subchondral bone plate region [44,46,48,49]. Osteochondral junction leakage (or the subchondral bone plate leakage) may compromise joint lubrication and leads to tribological challenges especially when combining with meniscectomy, because the osteochondral junction leakage provides an additional outflow pathway for fluid, leading to a more rapid fluid depressurization of the cartilage tissue over time after loading [49].

To date, the specific relationship between effects of increasing meniscectomy and its interaction and dependence on subchondral bone plate conditions remains largely unexplored. This study aims to investigate the interaction between varying degrees of meniscectomy and healthy (normal) and diseased osteochondral junction conditions. Quantification of this interaction will help us assess the dependence of the effect of increasing meniscectomy on osteochondral junction health, as depicted in schematic diagram in Fig. 1.

To achieve this aim, we will utilize a computational model of cartilage lubrication [25,49–51] to predict joint lubrication with increasing degrees of meniscectomy for different osteochondral junction leakage conditions. This model simulates joint lubrication behaviors by integrating sub-models of (i) the joint contact gap (the space between the tibia and femur cartilage in the synovial cavity), (ii) the cartilage tissue, and (iii) subchondral bone plate. By this means, our coupled model can capture the biomechanical effect of meniscectomy in joints with different osteochondral leakage. By elucidating consequences of the potential interplay between these two joint conditions on cartilage lubrication, we hope to ultimately provide some useful insights to enable better clinical management for patients with joint disorders such as meniscal injuries and osteochondral junction diseases.

2. Materials and methods

2.1. Study overview

This study investigates the impact of the degree of meniscectomy and ScBP health on joint lubrication using our previously published computational model [25,49–51]. An overview of the study is presented in Fig. 2. We have chosen to employ the multi-component joint model from our prior research, as it incorporates aspects of cartilage tissue behaviour, contact gap flow and subchondral bone plate leakage.

The primary variables for investigation in this study are (i) the loading area (which varies based on the degree of meniscectomy) and (ii) the osteochondral junction permeability ratio (expressed as an osteochondral junction permeability relative to the cartilage's permeability). That is, these two variables serve as the main inputs for parametric analyses reported here. The model predictions describe joint lubrication behavior through several engineering characteristics, namely peak average strain, the duration of mixed-mode lubrication and the time-dependent friction coefficient.

2.2. Multi-component coupled knee joint model

This study employs a multi-component coupled joint model, previously published by the authors [49]. This coupled model based on an upscaled poroelastic theory consists of three sub-models: the cartilage tissue, the joint contact gap, and the subchondral bone plate. Each of these sub-models will be briefly described below, including how they are coupled. The model was implemented by using the Poroelastic Module in COMSOL Multiphysics, configured in a 2D axisymmetric setting and meshed with 1204 triangle elements, the time-dependent solver with a general relative tolerance of 0.01 was utilized to solve the governing equations. Readers are referred to our previous publication [49] for comprehensive model development, otherwise, all the crucial aspects to understand the simulation and modelling configuration are presented in the following subsections.

For the current investigation, we adapted this existing model by introducing modifications to account for the effects of varying degrees of meniscectomy on the joint loading environment and the flow condition of the subchondral bone plate, which involves adjusting the input parameters and a more comprehensive analysis.

Specifically, in cartilage tissue model and contact gap model, the modifications were made by adjusting the loading contact area to simulate the effect of degree meniscectomy. Whereas in subchondral bone plate model, the modifications were made in varying the permeability to simulate different flow conditions of ScBP [46,49].

2.2.1. Governing equations

The sub-models described below are governed by a set of common equations.

Momentum conservation governs the force balance in each of the sub-model by neglecting the body and inertia forces [19,49].

$$\nabla \bullet \boldsymbol{\sigma}_t = \mathbf{0} \tag{1}$$

where $\boldsymbol{\sigma}_t$ is the total stress (Cauchy stress tensor of solid and fluid,

$\boldsymbol{\sigma}_t = \boldsymbol{\sigma}_{solid} + \boldsymbol{\sigma}_{fluid} = \boldsymbol{\sigma}_E - p\boldsymbol{I}$), $\boldsymbol{\sigma}_E$ is the effective stress of deformed solid phase, p is the fluid pressure, and $\boldsymbol{I}$ is the identity tensor.

The constitutive relations are employed in the system to describe the

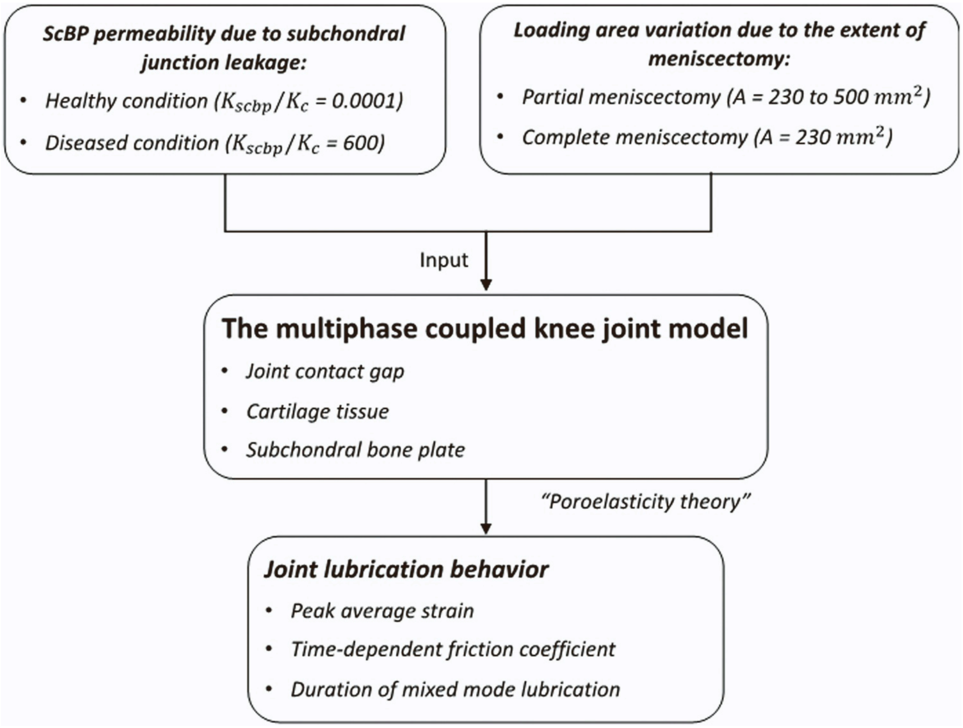

Fig. 2. Overview of the study. where $\boldsymbol{K_{scbp}}$ is osteochondral junction (subchondral bone plate) permeability; $\boldsymbol{K_c}$ is cartilage permeability; A is the loading area.

relationship between stress and strain in the system as detailed in the following Sections 2.2.2, 2.2.3 and 2.2.4.

Darcy's law describes the flow of fluid through a porous medium.

$$\boldsymbol{v}_d = -\boldsymbol{K}\nabla \boldsymbol{p} \qquad (2)$$

where K [m^2/Pa•s] is the hydraulic permeability in each region [21,46,52]. K_{ScBP} = hydraulic permeability in subchondral bone plate region, K_C = hydraulic permeability within cartilage, and K_g is the hydraulic permeability in the contact gap.

The continuity equations are fundamental in ensuring the conservation of mass within our system [53–57]. For cartilage tissue model and subchondral bone plate model, continuity equation is given as

$$\nabla \bullet (\boldsymbol{v}_d + \boldsymbol{v}_s) = \boldsymbol{0} \qquad (3)$$

where $\boldsymbol{v}_d$ is Darcy's velocity for fluid component relative to the solid phase, $\boldsymbol{v}_s$ is the solid phase velocity.

2.2.2. *Cartilage tissue model*

The cartilage tissue model is based on an upscaled poroelastic theory, in which cartilage is considered as a fully saturated deformable porous medium with both incompressible interstitial fluid and solid phases [49,51,58]. This model incorporates an empirical relationship that accounts

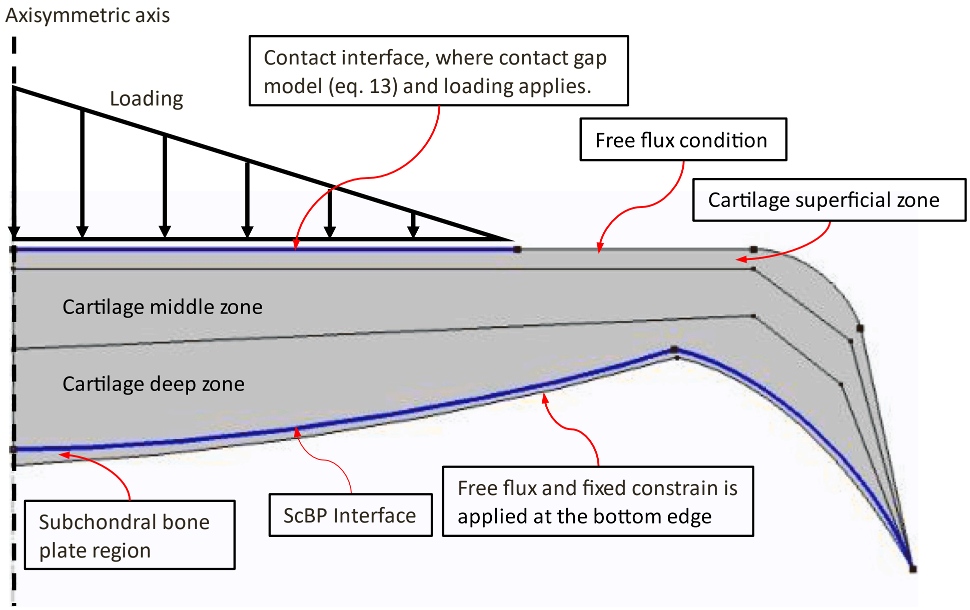

Fig. 3. Boundary conditions for the joint model.

for osmotic pressure and ion effects [50,59], linking the aggrecan concentration to mechanical properties of the cartilage tissue, including aggrecan-dependent stiffness and aggrecan-dependent permeability [46,52]. As aggrecan concentration and collagen organization vary across different depths and different zones of cartilage tissue, as illustrated in Fig. 3, so too do these mechanical and permeability properties. Additionally, the model captures the cartilage-specific characteristics of compression and tension nonlinearity.

The total stress (Cauchy stress tensor) for cartilage tissue model is,

$$\boldsymbol{\sigma}_t = \boldsymbol{\sigma}_E^s - p\boldsymbol{I} \tag{4}$$

where effective stress of solid matrix ($\boldsymbol{\sigma}_E^s$) resulting from solid deformation due to loading, assuming small element rotation, can be expressed as follows,

$$\boldsymbol{\sigma}_E^s = \frac{2}{J^s}\boldsymbol{F}^s \bullet \frac{\partial \boldsymbol{U}(\boldsymbol{u}^s)}{\partial \boldsymbol{C}^s} \bullet \boldsymbol{F}^{sT} \tag{5}$$

where $U(\boldsymbol{u}^s)$ is the strain energy density (Helmholtz energy per unit volume), and $\boldsymbol{F}^s$ is deformation gradient of solid phase, and $\boldsymbol{C}^s = \boldsymbol{F}^{sT} \times \boldsymbol{F}^s$ is right Cauchy-Green solid deformation tensor of solid phase, and $J^s = \det(\boldsymbol{F}^s)$ is the volume change of solid phase which is the jacobian determinant of the deformation gradient of the solid phase [60]. Note that the details of the solid phase constitutive relation and the compression-tension nonlinearity have been derived in the author's previous publication [50], readers are advised to refer to that for further details.

2.2.3. *Contact gap model*

The cartilage contact gap model represents the fluid flow in the contact gap, and includes fluid exchange between the contact gap and cartilage tissue. The contact gap is treated as separate porous medium composed of interconnected pores created by the asperities on the cartilage surfaces (i.e. the tibial, meniscal and femural cartilage surfaces). In this study, we use the same contact gap model as in our previous publication, but with modifications to the contact area to account for the changes in the loading area following meniscectomy [25].

For joint contact gap model, continuity equation is given as below,

$$\frac{\partial \boldsymbol{\varepsilon}_v^g}{\partial t} + \nabla \bullet \boldsymbol{v}_d = \boldsymbol{s} \tag{6}$$

where s is the spatially variable rate of change of the fluid exchange per unit volume, $\frac{\partial \varepsilon_v^g}{\partial t}$ is the rate of change of contact gap volumetric strain. The volumetric strain of the contact gap is related to the gap height h, the constitutive relationship for the gap height h and total stress $\boldsymbol{\sigma}_t$ was proposed based on experimental studies for the human cartilage [61,62]. This relationship was represented as $h = h_0 e^{\sigma_{Eg}/\beta}$, here σ_{Eg} is the solid contact stress in contact gap model, β is the cartilage surface asperity stiffness and h_0 is the initial undeformed gap height. Further explanation of this model can be found in references [25].

2.2.4. *Subchondral bone plate model*

The subchondral bone plate sub-model represents the flow status of ScBP for the cartilage sub-model, and so indirectly influences knee joint lubrication. For the purposes of this study, we have modified the ScBP model to incorporate different permeability values, reflecting the varying flow status of the osteochondral junction.

It's important to note that the solid phase of the subchondral bone plate is treated as a linear elastic solid. This is due to the bone's high stiffness and the relatively small physiological load compared to its strength. This treatment contrasts with that of the cartilage, which has a more complex constitutive equation due to the non-linear elasticity in compression and tension.

The constitutive relationship for the solid phase in ScBP model is presented below.

$$\boldsymbol{\sigma}_E^{ScBP} = \boldsymbol{E}_{ScBP} \bullet \boldsymbol{\varepsilon} \tag{7}$$

where E_{ScBP} is the Young's modulus, $\boldsymbol{\varepsilon}$ is the ScBP vertical strain.

2.3. *Boundary conditions, loading, and model constraints*

This study employs an axis-symmetric condition in the joint compartment, an assumption supported by experimental observations that reveal approximately axisymmetric stress contours [63]. The axisymmetric condition extends across compartments as illustrated in Fig. 3, which also shows the boundary conditions and model constraints.

The fluid phase boundary condition is the ambient (i.e., zero) fluid pressure at the edge of the contact gap and trabecular bone (i.e., at bottom of the subchondral bone plate), while remaining surface areas have a no flux boundary condition. The solid phase is subject to a fixed constraint condition everywhere except on the cartilage contact surface.

Based on the MRI measurements [64] and experimental deformation contours [63], a conically distributed compressive stress is employed in the study, which is the same loading approach used in the previous studies [49,51]. The loading configuration for cases with a normal adult joint is shown in Fig. 3 (and Fig. 1). However, as menisci surface area is removed (as shown in Fig. 1), the spread of the loading area decreases. The study commences with the application of a step-loading to the joint at time zero. Immediately following the loading, the load is fully taken by the fluid pressure in both the contact gap and the cartilage (as shown in Fig. 3). An initial undeformed gap size is assigned to the contact gap model.

Note that for the coupling of each sub-model, pressure continuity and flux continuity are observed at each interface.

2.4. *Parameters and assumptions*

The study focuses on two main attributes as primary input variables: the permeability of the osteochondral junction (or subchondral bone plate, ScBP) and the extent of meniscectomy (recall Fig. 2). The approach taken is to define a normal young adult joint as a control and then vary the primary model inputs away from this normal case. The specific model parameters used are shown in Table 1, categorized by osteochondral junction status, followed by the degree of meniscectomy. Below we present arguments for why the range of model values corresponding to degree of meniscectomy and osteochondral junction health included in this study are appropriate to capture the likely scenarios.

Here we assume that the ScBP includes the region immediately underneath the porous articular cartilage tissue and above the subarticular spongiosa region. Under normal and healthy conditions for young adults, the ScBP region is usually considered to be effectively impermeable. Previous studies estimated this permeability to be very low, around $10^{-19} \sim 10^{-20}$ m^4/Ns, which is 3–4 orders of magnitude smaller than the permeability of normal adult cartilage [49,65,66]. Therefore, we assume a relative permeability ratio between ScBP and cartilage to be 0.0001 to represent the healthy, near-impermeable ScBP conditions. This assumption is consistent with the authors' previous publication [49].

However, in the case of injury or disease states such as osteoarthritis, osteoporosis, and aging-related degenerative changes, the ScBP can become porous [48,67]. This increased porosity leads to a much higher permeability in the ScBP, and so significant fluid exchange can occur between the cartilage tissue and the subarticular spongiosa region. Previous studies on older adults indicate that the subchondral bone plate region may exhibit permeability increases 350 – 600 times higher than hyaline cartilage [19,46,49,65] or 5–6 orders of magnitude higher than that of healthy ScBP. In this study, we assume a relative permeability ratio between ScBP and cartilage of 600 to represent a diseased/leaking subchondral bone plate. Note that, in this study, diseased ScBP means the osteochondral junction leakage condition.

Table 1

Cases studied for the effect of meniscectomy under healthy and diseased subchondral bone plate condition (osteochondral junction leakage) with key parameters [19,46,63,65,66,71–73].

Parameters	**Effect of meniscectomy under healthy ScBP condition**			**Effect of meniscectomy under diseased ScBP condition**		
	Case 1.1*	Case 1.2	Case 1.3	Case 2.1	Case 2.2	Case 2.3
	Intact meniscus	50% partial meniscectomy	Complete meniscectomy	Intact meniscus	50% partial meniscectomy	Complete meniscectomy
Loading Area (mm^2)	500	365	230	500	365	230
Relative permeability, K_{ScBP}/K_c	0.0001 Healthy ScBP			600 Diseased ScBP		

*Note, Case 1.1 is the control case; 50% partial meniscectomy means 50% of the meniscus is surgically removed

The meniscus helps distribute load across the knee joint during various daily activities [6,7], and removing all or part of the meniscus has the biomechanical implication. The presence of meniscus ensures that the load is spread over a relatively large contact area, reducing localized concentrated stress, and preventing wear [18]. When the meniscus is removed, the joint contact area is notably reduced. This reduction in loading area can lead to the load concentrating on a smaller portion of cartilage, resulting in elevated contact stress. As a result, one can expect accelerated wear on the cartilage surface compared to a healthy joint. This is because the cartilage will experience increased shear and compressive forces at the contact surface without the load-distributing function of the meniscus. Additionally, the absence of the meniscus can also disrupt the flow path and distribution of synovial fluid [3,20], which plays a role in nourishing and lubricating the surface [2,19]. Reduced lubrication and nourishment from the synovial fluid will further exacerbate cartilage wear at the contact surface.

The synovial fluid is a viscous and non-Newtonian fluid that exhibits shear-thinning effects [68], its viscosity decreases with the increases of shear rates, at higher shear rate, it behaves more like a fluid with low viscosity; while at the low shear rate action such as walking or one-leg standing in the context, it exhibits a higher viscosity [68]. For the scope of the current study, simulating cartilage tissue experiencing the static compressive load, the shear rate is expected to be very low, hence we assume a constant corresponding viscosity value being 1 Pa•s for synovial fluid. Note that this value of viscosity for static loading has also been used in previous studies [25,69,70].

A wide range of experimental reports exists for the tibia-femoral contact area with intact meniscus [63,71–73], with total contact area measurement ranging from as high as 2000 mm^2 to as low as 520 mm^2 (i.e. total area in both medial or lateral compartment) [63,71–73]. In this study, we assume equal contact area in both medial and lateral compartments (with measurements taken at 0° flexion), and assume an intermediate surface area of 500 mm^2 (for only one compartment) to represent the case where the meniscus remains intact, consistent with Stephen et al.'s measurements [71]. The tibia-femoral contact area on the cartilage surface after complete meniscectomy is consistently reported to be around 230 mm^2 [71,72], hence the contact area of 230 mm^2 is used to represent complete meniscectomy case.

Compartment contact area (and contact stress) and the degree of meniscectomy has previously been experimentally found to be proportional [71,74,75]. We assume a similar proportionality in the modeling, where partial meniscectomy is represented by a contact area between 230 and 500 mm^2. The contact area decreases proportionally as the meniscus is removed. For the cases investigated and shown in Table 1, the total load applied on each compartment (lateral/medial) assumed to be the same across all cases. We model a scenario reflective of a human standing on one leg. To simulate this condition, we apply a static compression force of 820 N to a joint compartment for a duration exceeding 3 h to ensure the system reaches equilibrium condition [19]. The force value of 820 N on each compartment in the knee joint during one legged standing is derived by assuming 2.59 times a body weight force of 650 N [76]. In this study, we link the meniscectomy with a reduction in the joint contact area, and we assume the use of loading area variation (on cartilage contact surface) represents the degree of meniscectomy. Note that the amount of damaged meniscus requiring removal in this study is limited to damaged meniscus in the W-W zone and R-W zone (Fig. 1d) only.

When modelling the impact of the increasing meniscectomy on patients with normal and abnormal osteochondral junctions, an additional important simplifying assumption is made. It is assumed that the joint contact surfaces (cartilage surfaces) remain congruent across all cases, even for injuries/disease cases. This assumption allows for isolating the effect of the increasing degree of meniscectomy under healthy/diseased osteochondral junctions and drawing clear conclusions about its impact on joint lubrication behaviors. However, authors acknowledge that cartilage surfaces may exhibit time varying degrees of wear associated with other joint injuries/diseased and this should be considered in future research.

3. Results and discussion

The objective of this study is to assess the combined effect of the degree of meniscectomy and ScBP health condition on joint lubrication. Six typical cases (as shown in Table 1) are selected to demonstrate the results, including the time-dependent peak average strain, time-dependent friction coefficient, the mixed-mode lubrication duration, and the relationship between the extent of meniscectomy under different ScBP health conditions.

3.1. Time-dependent peak average strain

The peak average strain in this study is defined as the ratio of the highest value of deformation occurring at the contact center of the cartilage and its original thickness of cartilage, it is a crucial metric to provide insight into the mechanical state of the cartilage tissue, helping to identify the likely site of cartilage damage and so early onset of OA [29,77,78]. As shown in Fig. 4(a), it is predicted that the cases of complete meniscectomy have the highest value of peak strain among all other cases during the period of sustained load bearing (standing), followed by partial meniscectomy cases and then normal meniscus cases. This result aligns with the previous research on the consequences of meniscectomy [10,42,51]. At the steady state, the joint with normal meniscus has a peak average strain of approximately 0.26, consistent with values reported in the previous experimental study [79]. The steady state cartilage peak strain for 50% partial meniscectomy is estimated to be around 0.3. In the case of complete meniscectomy, at the steady state, the estimated peak average strain increases to 0.35 (as shown in Fig. 4a), representing a 35% increase compared to normal meniscus case (control). This result is in good agreement with the experimental study by Song et al. that reported a 35% increase in the steady state maximum strain for meniscectomies knees as compared to normal knees [80]. Note that this study assumes for a constant aggrecan content in the cartilage. In practice, the aggrecan content can decrease with advancing age and in disease states, which can further influence observed strain patterns.

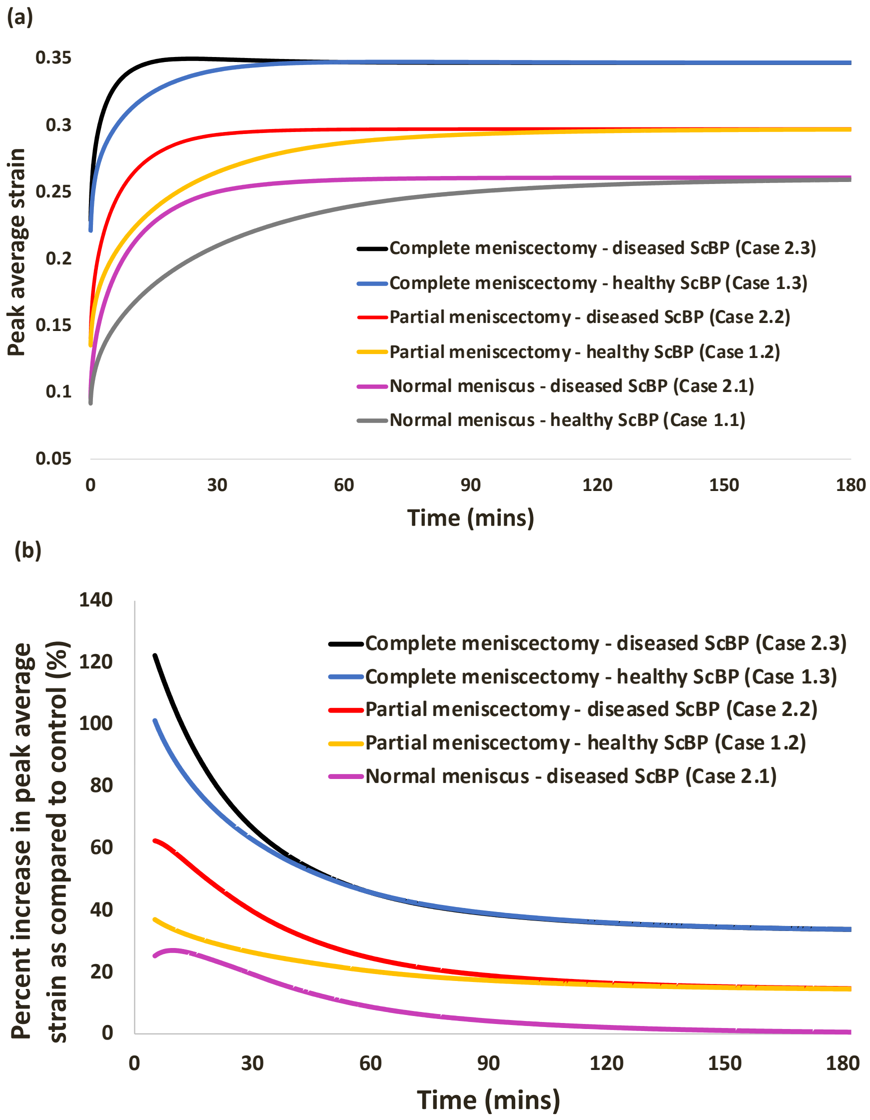

Fig. 4. (a) Peak average strain versus time (mins); (b) Percent increase in peak average strain for each case as compared to control case (time-dependent), where percent increase is represented by $[\boldsymbol{\varepsilon}(\boldsymbol{t}) - \boldsymbol{\varepsilon}_{\boldsymbol{control}}(\boldsymbol{t})]/\boldsymbol{\varepsilon}_{\boldsymbol{control}}(\boldsymbol{t})$, and $\boldsymbol{\varepsilon}$ is the peak cartilage contact strain.

Under the same ScBP health condition category, the peak average strain curve steepens (i.e., has a higher slope) with an increase in the degree of meniscectomy. This is particularly evident for the condition of a healthy ScBP (case 1.1–1.3). However, for the diseased ScBP condition (case 2.1–2.3), where a fluid leakage path exists between the cartilage tissue and the subarticular spongiosa area, the increase in steepness of the early peak average strain curve is less pronounced when the degree of meniscectomy increases. This is because compromised pressurization of the cartilage upon loading has already taken place due to the leaking ScBP.

For the same degree of meniscectomy, increased fluid leakage in the ScBP results in a more rapid increase in peak average strain. As shown in Fig. 4(a), the cases with diseased ScBP reach steady state more quickly than those with healthy ScBP conditions (case 2.3 compared to 1.3, case 2.2 compared to 1.2, case 2.1 compared to 1.1).

As demonstrated in Fig. 4(b), the normalized peak average strain exhibits a faster increase in the initial stages of loading for diseased ScBP cases, compared to heathy ScBP cases. In the event of a complete meniscectomy, the initial normalized peak average strain compared to the control case (normal meniscus at healthy ScBP condition) is 120% higher for diseased ScBP and 100% higher for a healthy ScBP. Conversely, in the case of a 50% partial meniscectomy, these values adjust to 60% higher and 40% higher respectively.

A diseased ScBP does not lead to a higher steady state cartilage strain under equilibrium loading. Rather the diseased ScBP reduces the time needed for the tissue to reach a steady state (high strain value), exposing the cartilage tissue to higher strains sooner after starting the one-leg standing activity (or indeed, for any activity involving locomotion). With the duration of one leg-standing, one should expect that cartilage tissue with diseased ScBP will be exposed to high strains more as compared to normal tissue (and similarly, for any activity involving locomotion). It is tempting to then suggest that patients with such conditions should limit the duration of the activity (e.g., standing, walking, running) to reduce exposure to higher stress and strain levels on the cartilage tissue, because such conditions can result in a shortened timeframe to reach steady-state contact strain (or indeed, steady-state cyclic loading), potentially leading to joint damage when initiating motion or at early stages of motion (e.g., standing, walking, running).

We would note instead that, as cartilage is also known to be stimulated by strain (or strain rate) to synthesis new ECM, a more advanced model combining cartilage damage and repair processes is needed before making such a firm conclusion [19,81,82]. That being said, it is possible to find reported observations that align with our prediction. For example, relieving stress levels has been shown to enable repair chronic bone marrow edema is effective towards OA treatment and avoiding acceleration of joint degeneration [83], so clearly there is an optimal amount of activity.

It should also be noted that, our study focuses on the static loading through one-leg standing, and we acknowledge it differs from the dynamic motions like walking and running. However, we assume that implications from the results of one-leg standing infer similar general observations on cartilage tissue strain, and so can be cautiously applied to the dynamic scenarios. In dynamic activities, motion begins and returns in a relatively static state, similar to one-leg standing [60]. Therefore, our results provide some initial understanding of the initial loading phase in the motion. For example, early onset of peak average strain observed in cases of complete meniscectomy in the static loading suggests higher strain levels during the initial phase of motion under both static and cyclic loading. We indeed acknowledge that the transition from static to dynamic scenarios is complicated, particularly given reciprocal unloading of the joint while walking and running. While our study provides some preliminary insights into locomotion activities, more future research should be conducted to better understand these dynamics.

As previously highlighted, peak average strain plays an important role in determining the potential for cartilage damage and early onset of OA. Results from Fig. 4(b) show that a complete meniscectomy, particularly under the diseased ScBP condition, leads to a significant increase in peak average strain, with a 120% increase compared to control conditions. Although this study focused primarily on one-leg standing scenarios (which involve static compressive load), it is plausible that more strenuous activities such as rising from a chair, or climbing stairs [84], could result in higher strains than reported here. This is especially true for complete meniscectomies under diseased ScBP conditions, which could further increase the risk of cartilage damage and cell death. These findings highlight the importance of preserving meniscus, avoiding unnecessary meniscectomies, and maintaining a healthy ScBP to prevent early development of OA.

3.2. *Time-dependent effective friction coefficient*

During the joint motion, frictional force arises at the joint contact interface. This motion inevitably results in some mechanical energy lost as heat but also causing surface degradation and wear [19]. This wear is a result of dissipative process at the contact surface [19] including adhesive wear (stiction, i.e., increased static friction) [35], stick-slip wear [85], surface abrasion wear [86]. Collectively, these processes result in significant wear on the (cartilage) surface asperities and a decrease (loss) of collagen content, which changes the surface properties [19], with time-dependent (effective) friction coefficient being one of the most important surface properties that change when the surface wears. When the applied load remains constant as in this study, any increase in friction coefficient will influence the wear rate, and as the wear continues, the frictional force progressively increases, creating a positive feedback process.

Considering the relative load support between the cartilage solid matrix asperities and interface gap fluid, the (time-dependent) effective friction coefficient is a vital determinant of joint lubrication efficiency. The effective friction coefficient provides a measure of boundary friction resistance between two opposing cartilage surfaces during sliding motion. and serves as a crucial quantitative indicator of effective lubrication, because a small effective friction coefficient means boundary lubrication plays a minor role, while a large effective friction coefficient means boundary lubrication plays the dominant role. How the magnitude of boundary lubrication changes over time sheds light on likely joint wear mechanisms over time [87].

In the current context of joint under static compressive load, a higher friction coefficient combined with prolonged exposure to high friction suggests an increased likelihood of cartilage surface wear. Conversely, if effective lubrication is maintained (evidenced by a prolonged period of low friction coefficient), the joint is likely to exhibit greater wear resistance and is less prone to surface wear. The wear of cartilage in this context can largely be attributed to factors such as increased contact stress due to meniscectomy, disruptions to the synovial fluid flow at the contact gap (resulting from meniscus removal), and rapid fluid exudation due to osteochondral junction conditions. Collectively, these factors contribute significantly to the wear process as discussed in the following sections. For the purpose of our simulation, it is important to note that we are assuming consistent surface conditions, such as roughness and surface wear, throughout the simulation, an increase in friction coefficient value indicates a decline fluid load support, and this increase suggests a heightened likelihood of cartilage surface damage and the early onset of OA (initially causing an increase in surface roughness).

In the current context of numerical simulations, for patients with conditions such as meniscectomy and ScBP disease leading to increased fluid conductivity, the theoretical effective friction coefficient serve as a useful quantitative indicator for physiologically-safe levels of exercise, or the duration of each individual activity for patients. We note the theoretical friction coefficient calculated is realized when motion is initiated [58,88].

The cartilage surface effective friction coefficient μ_{eff} is a term typically used in the theoretical analysis of saturated porous media [89,90] based on biphasic poroelastic lubrication theory [91], it is a term typically employed to model the experimentally observed behavior of the contact interface to explain the experimental observations for the apparent friction coefficient. The equation for effective (contact) friction coefficient is presented below in this section.

$$\boldsymbol{\mu_{eff}} = \boldsymbol{\mu_{eq}} \bullet (\mathbf{1} - \boldsymbol{W^f}) \tag{8}$$

where μ_{eq} is the average equilibrium friction coefficient taken as 0.3 from previous experiments [58,92,93], which is based on experimental measurements made when deformations are complete (i.e., at equilibrium condition). W^f is the fraction of fluid load support defined as integral of total stress minus effective stress over contact area divided by the integral of total stress over contact area.

Fig. 5(a) presents the time-dependent friction coefficient over time for six typical cases listed in Table 1. In the control case for a healthy joint condition (case 1.1), it takes approximately 3 h for the friction coefficient to reach equilibrium, consistent with previous experimental findings [58,94–96]. Like peak average strain, the slope of friction coefficient curve prior to reaching equilibrium is affected by the degree of meniscectomy and the health of ScBP. The steeper the slope, the shorter the time to reach a higher friction coefficient. As shown in Fig. 5(a), the higher the degree of meniscectomy, the steeper the slope. Under the healthy ScBP conditions, the degree of meniscectomy has a significant impact on slope change, but this impact is less pronounced under diseased ScBP conditions. Hence, the effect of degree of meniscectomy also depends on the health condition of ScBP. Regardless, overall, cases with diseased ScBP exhibit a steeper slope or rate of increase in the friction coefficient, compared to cases with healthy ScBP.

The dynamic nature of friction coefficient provides insights into how lubrication effectiveness changes during the simulation, factors like meniscectomy or a diseased ScBP can significantly alter this coefficient and leading to a compromised lubrication. Such changes can lead to increased wear rates, altered cartilage biomechanics, and a more likely risk of OA onset.

Fig. 5(b) shows the percentage increase in the friction coefficient compared to the control case. Case 1.2 and 1.3, which represent partial and complete meniscectomy under healthy ScBP condition, demonstrate that the degree of meniscectomy has a significant impact on the time-dependent friction coefficient throughout the one-leg standing. By comparing the case 1.2 and 2.2, and case 1.3 and 2.3, it becomes clear that the health condition of ScBP (osteochondral junction leakage) has a significant impact as well, particularly during the early stage of the standing activity. At 30 min after loading, the model predicts a 55%

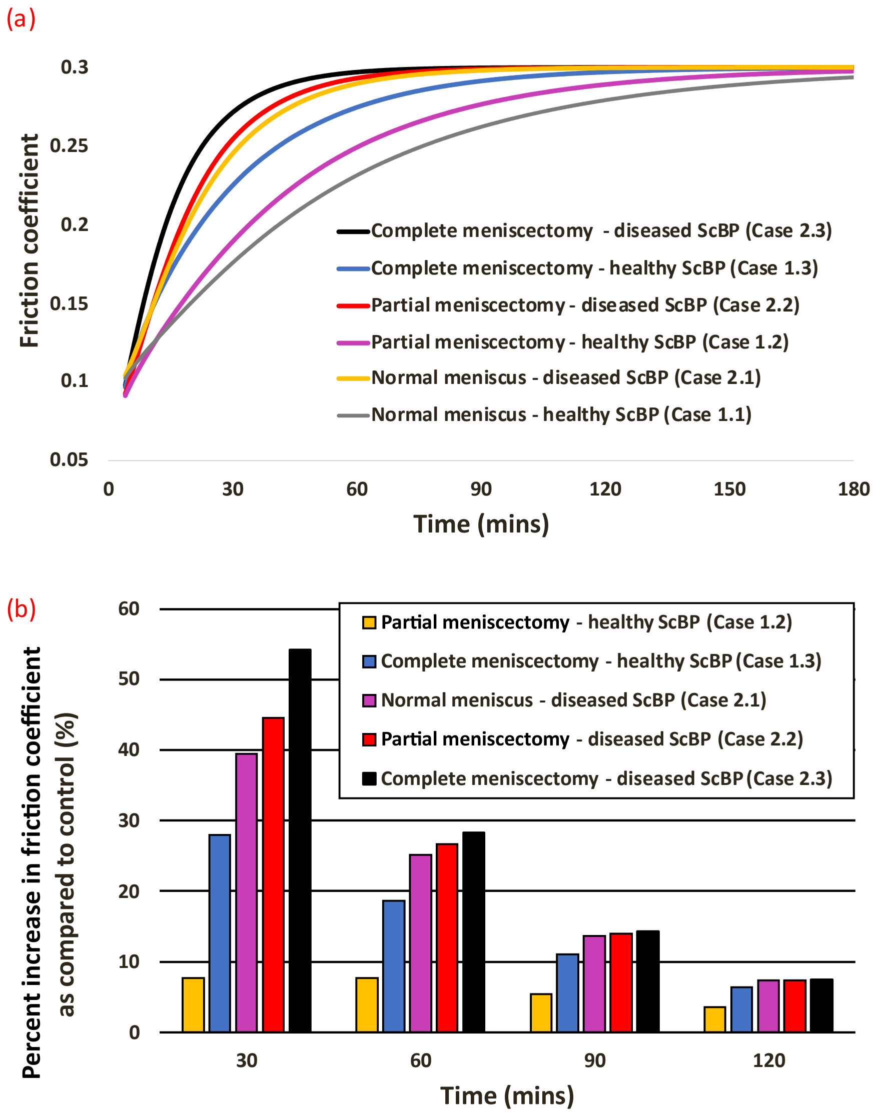

Fig. 5. (a) Time-dependent (effective) friction coefficient; (b) Percent increase in friction coefficient in 30, 60, 90, 120 mins.

increase in friction coefficient for the complete meniscectomy under a diseased ScBP condition as compared to control (so one might expect a doubling of wear rate at the early stage of activity), while a 28% increase is predicted for complete meniscectomy under a healthy ScBP condition. For partial meniscectomy, the model predicts a 7% and 44% increase of friction coefficient for healthy and diseased ScBP condition respectively at 30 mins after loading, with respect to the control case. However, as time progresses, the impact of ScBP leaking condition become less significant, as seen at 90 min or 120 min after loading.

This theoretical analysis suggests that ScBP health condition plays an important role at the early stage of standing activity rather than later with regards to its impact to the tissue properties. Consequently, a higher friction coefficient is likely to occur in the joint upon the initiation of activity (and indeed, a higher friction coefficient is expected during activity). This higher friction coefficient can lead to increased rates of wear, and potentially lead to early onset of OA (e.g., roughening of the cartilage surface is often reported as an early sign of OA). This is particularly common in cases of post-traumatic (i.e., knee injury) early onset OA [97].

The results emphasize the significance of preserving meniscus and a healthy ScBP, as they both help to maintain a low contact friction coefficient as possible. In scenarios where the ScBP is compromised or diseased, the question of whether to perform a partial or complete meniscectomy become less crucial. This is because the lubrication capability, is already compromised by the diseased ScBP, as shown in Fig. 5. This highlights the importance of properly diagnosing joint conditions for meniscectomy pre-operative planning.

3.3. Mixed-mode lubrication duration

During daily activities, the articular joint typically operates in mixed-mode lubrication regime which is described as a “co-existence” of both boundary lubrication and hydrodynamic lubrication [19,25]. Mixed-mode lubrication duration is important for evaluating and advising patients on the physiologically-safe level or duration of the daily activities following meniscectomy surgery. The mixed-mode lubrication occurs when the opposing cartilage tissue are in close, and asperities contact occurs (i.e. boundary lubrication mode), while there is still a thin pressured film of fluid present (i.e., hydrodynamic lubrication mode). The duration of mixed-mode lubrication, in the current context, is defined as the time from start after initial asperity contact to the point when the fluid load support diminishes to a small value (here the arbitrarily small value is set to be 5% of total step loading i.e., a reduction of 95% compared to the initial step change in fluid pressure at the cartilage surface. Predicting the duration of the theoretical mixed-mode lubrication is crucial when quantitatively estimating the friction coefficient on initiating motion. The duration of mixed mode lubrication is a critical value when evaluating the post-surgery functional lubrication status for patients who have undergone meniscectomy with a range of underlying ScBP health (permeability) conditions, and the theoretical estimate when standing is probably a useful indicator of what is likely to happen during activities involving motion.

As shown in Fig. 6(a), when standing on one leg, the mixed-mode lubrication duration for healthy joint (case 1.1) is estimated to be 140 min, which aligns with previous experimental measurement that shows a 95% reduction in fluid load support can take between 133 min and 160 min [58,98]. It is normal for the interstitial fluid pressure to dissipate over several hours [51,58], but if there is joint injury present this process can occur much faster, leading to shorter mixed-mode duration. The comparison between healthy and diseased ScBP in Fig. 6 (a) highlights the significant impact of a diseased ScBP on mixed-mode lubrication duration, as it reduces the duration significantly across all the cases of meniscectomy. Under the normal meniscus condition, the mixed-mode duration is significantly reduced from over 2 h to less than 1 h when ScBP is leaky under a diseased condition. The similar effects were also observed under cases of partial and complete meniscectomy. This is likely to be physiologically important, particularly for individuals involved in physical labor or strenuous activities. This theoretical estimate suggests that they may need to adjust their work period to allow sufficient recovery time for cartilage before they do some work again. These findings highlight the importance of maintaining a healthy ScBP for proper joint function, as a leaky ScBP leads to quicker fluid dissipation and possibly cartilage surface wear and damage.

Observed from the dashed line in Fig. 6(a), there appears to be a correlation between the mixed-mode lubrication duration and the amount of meniscus removal (case 1.1 and 2.1 for no removal, case 2.1 and 2.2 for 50% removal, and case 2.3 and 3.3 for 100% removal). To further explore this correlation, a parametric study was conducted as shown in Fig. 6(b), for both healthy and diseased ScBP conditions. The result reveals a correlation between normalized mixed-mode duration, represented as a percentage reduction compared to the control case, and the extent of meniscus removal. In the healthy ScBP condition, complete meniscectomy led to a roughly 50% reduction in mixed-mode lubrication duration compared to the control case (case 1.1).

Making a conservative estimate based on the results presented above, this suggests that for patients with healthy ScBP condition who undergo complete meniscectomy, post-surgery activity level or duration of standing be reduced by 50%, as compared to healthy joint cases, to

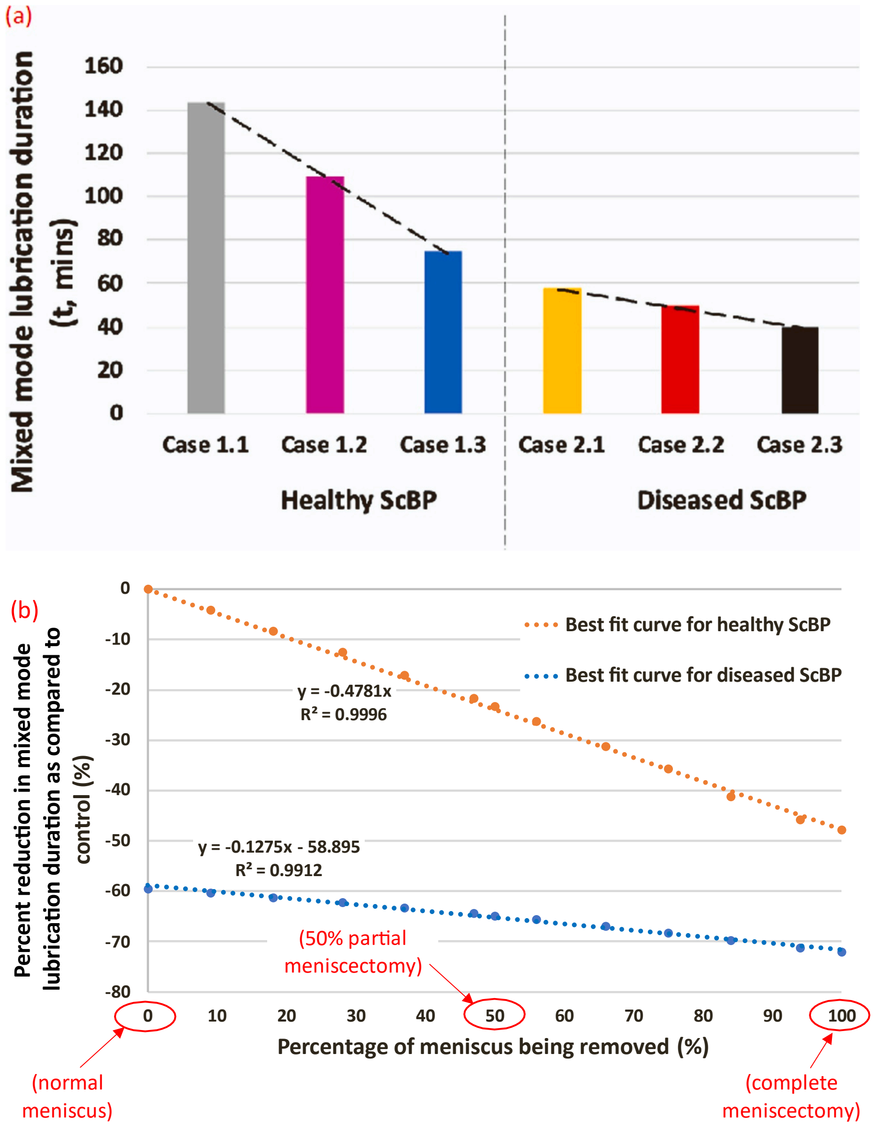

Fig. 6. (a) Mixed mode lubrication for different cases; (b) Proportionality between the reduction in mixed mode lubrication duration relative to control (case 1.1) and the degree of meniscectomy.

minimize damage to cartilage surface. In contrast, under the diseased ScBP condition, normal meniscus cases result in a 59.6% reduction in mixed-mode lubrication duration compared to control case, and it increases to 72% at complete meniscus removal. Conservatively, this suggests that for patients with diseased ScBP condition with no meniscus removal, the level of the activities (primarily standing) should be reduced by roughly 60%, as compared to normal individuals. However, for patients with diseased ScBP condition who undergo 100% meniscus removal, the duration should be reduced by 72%, compared to healthy knee. By comparing the overall normalized mixed-mode lubrication duration in Fig. 6(b), the reduction in mixed-mode lubrication duration is greater in diseased ScBP condition compared to healthy ScBP condition. This suggests that the condition of ScBP plays an important role on the functional effect of meniscectomy on mixed-mode lubrication duration.

It can be concluded that the removal of the meniscus (the degree of meniscectomy) has a significant impact on mixed-mode lubrication duration, with greater removal leading to a greater reduction in mixed-mode duration. The impact of the degree of meniscectomy on joint lubrication also depends on the condition of ScBP, with a healthy ScBP condition leading to a larger impact of the degree of meniscectomy on mixed-mode duration compared to a diseased one as shown in Fig. 6(b). Therefore, the results suggest that more caution should be taken when performing meniscectomy surgery on patients with a healthy ScBP, to preserve as much as meniscus as possible during the surgery, as any additional removal of meniscus can have a significant impact on joint lubrication performance [99].

4. Limitations

This study has limitations, particularly its simplification of complex joint biomechanics by employing a single, simplified joint geometry and a uniform total load in the model. This overlooks the variations in load and dimensions across different knees. Additionally, the study assumes a proportionality between joint loading area and the degree of meniscectomy. Although useful as an approximation, this may not always be accurate due to individual variations in meniscal anatomy, surgical techniques, and the type of meniscal tear, such as those leading to the loss of hoop strain.

Furthermore, the study considers only meniscectomy and ScBP leakage, neglecting the potential for patients to have concurrent joint changes. Consequently, the study's results are not directly applicable to any specific patients undergoing meniscectomy, as their post-surgery outcomes may be influenced by patient specific conditions. To capture post-surgery outcomes more comprehensively after meniscectomy, future research should incorporate patient specific considerations, and other joint disease conditions, such as osteoarthritis, ligament damage, and tendon damage.

Moreover, to control for potential confounding variables and isolate the effect of the degree of meniscectomy and ScBP health, the study assumes uniform joint contact surface congruency across all considered cases. In patients with more complicated joint conditions, different levels of surface damage and wear might be present, which also warrant consideration in future studies.

Further, future research should consider varying dynamic loading scenarios (e.g., walking, running) to understand the impact of the degree of meniscectomy and ScBP condition on joint lubrication. Lastly, how the tissue is damaged, and repairs is also beyond the scope of the study but is needed to connect theoretical results to practical clinical situations.

5. Conclusion

The study investigated the effect of the degree of meniscectomy on joint lubrication for patients with healthy and diseased ScBP conditions. The major conclusions are summarized below.

1. The degree of meniscectomy significantly affects the amount of tissue deformation, with complete meniscectomy resulting in the highest steady state peak cartilage contact strain. In the case of diseased ScBP, the deformation occurs more quickly, which shortens the time required to reach the common final steady state deformation. This suggested that patients with higher degree of meniscectomy will have greater risk of cartilage damage.
2. Under healthy ScBP condition, the degree of meniscectomy has significant impact on the theoretical time-dependent friction coefficient at the initiation of motion, with greater degree of meniscectomy leading to faster increase in the theoretical friction following loading. However, this impact on friction is less pronounced with diseased/leaking ScBP condition, as these leaky joints already have short joint lubrication durations. This suggests the effect of the degree of meniscectomy on joint lubrication also depends on the health condition of ScBP.
3. This study indicates that a reduction in activity level (either load or duration) for patients who undergo meniscectomy surgery with different ScBP conditions may help prevent cartilage damage. As a conservative estimate based on these theoretical results, the post-surgery activity duration or level should be reduced by 50% for patients who under complete meniscectomy with healthy ScBP. For patient with diseased ScBP conditions, a 60% reduction in activity level is suggested for people with intact meniscus, and a 72% reduction is suggested for patients with complete meniscectomy.
4. The study provides an overall very general picture of how the degree of meniscectomy and ScBP health interact to affect joint lubrication. However, it is important to recognize that the computational model is primitive, and further, individual treatment plans need to be customized depending on patient's specific condition. While the model suggests potential trends, it doesn't offer specific recommendations for clinical practice, as these would need to be grounded in further research and the unique context of each patient's health.
5. As a final note of caution in using these results to inform clinical recommendations. Although it is tempting to apply some of the findings linking cartilage strain exposure to activity, specifically higher strain exposure to in diseased tissue, without a damage and repair model to accompany this finding we cannot say what the consequences to tissue health will be in an individual or patient cohorts. Strain is involved in both damage and repair processes, so long-term tissue health is determined by the balance between these two opposing processes. We can only say that on balance, the degree of meniscectomy and diseased ScBP, increases exposure to strain and higher friction contacts and that this should be taken into account when planning future studies and treatments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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