Striebeck Analysis Of Synovial Lubricants: Lubricating Mechanisms And Interaction Of Hyaluronic Acid And Lubricin

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Disclosures:
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Introduction: Intra-articular injections of both viscous agents and boundary lubricants have been presented as options to mitigate the progression of articular cartilage damage after the onset of osteoarthritis [1,2]. Specifically, hyaluronic acid (HA) has been used clinically and lubricin has proven effective in animal trials. Mechanically, these injections are predicted to lower the friction coefficient within a load bearing joint and consequently slow the propagation of damage at the articular surface. Tribologically, boundary lubricants and viscous agents are hypothesized to be effective through two different mechanisms - boundary lubricants affect boundary-mode lubrication and viscous agents facilitate transitions to mixed-mode and hydrodynamic lubrication. Further, interactions between HA and lubricin have been proposed, and investigated experimentally, but the mechanisms of such interactions with respect to lubrication mode are not understood [3,4]. In this study we probe the individual and combined effects of HA and lubricin across multiple modes of lubrication by generating Striebeck curves of lubricated cartilage.

Methods: Articular cartilage samples were extracted from the patellofemoral groove of neonatal bovines. A custom-built tribometer was used to measure friction coefficients of articular cartilage sliding against polished glass while bathed in a lubricant solution. Briefly, cylindrical cartilage samples were compressed to 20% strain and the normal load was allowed to reach equilibrium resulting in an average normal pressure of 91 kPa. Samples were articulated at sliding speeds from 0.1 to 10 mm/s. Lubricant solutions had three different HA groups: PBS (no HA), 500-700 kDa HA at 10 mg/ml, and a more viscous HA derivative (HYADD) at 8 mg/ml with dynamic viscosities of 1, 156, and 72038 mPas respectively. Lubricin conditions consisted of cartilage surfaces with endogenous lubricin extracted [5], surfaces left unaltered, and lubricin added to the lubricant in solution at a final concentration of 20 μg/ml. To reveal the mechanisms of the lubricants, data was plotted according to the Hersey dimension which is defined as: sliding speed * lubricant viscosity / normal pressure.

Results: HA presence decreased friction in the unaltered surface condition samples (i.e. samples containing endogenously bound lubricin) (Figure 1, left). For the 500-700 kDa HA, friction was considerably decreased with increased sliding speed. To analyze lubrication mechanisms, data was normalized to a Striebeck curve according to the Hersey dimension (Figure 1, middle). The Striebeck curve shows different lubrication modes including boundary, mixed and hydrodynamic lubrication. The continuity of all three lubricants along one curve reveals the role of HA by increasing viscosity to facilitate the transition between lubrication modes. To probe the role of HA further, a 5 mg/ml HA solution was used as a lubricant to obtain overlapping segments of the Striebeck curve (Figure 1, right). The data confirm the continuity of the Striebeck curve and HA’s role as a viscosupplement. Lubricin however was an effective boundary lubricant throughout both boundary and mixed lubrication modes (Figure 2). Removal of endogenous lubricin increased boundary friction by 22% and introduction of lubricin in solution reduced boundary friction by 50%. The interaction between HA and lubricin was analyzed by marking the transitions between lubrication modes. Specifically, the transition between mixed and hydrodynamic lubrication was noted at the minimum values of the Striebeck curve. The minima for different lubricin conditions occur at Hersey dimensions of 530 nm, 2900 nm, and 10 nm for unaltered, lubricin extracted, and lubricin in solution, respectively. This interaction between HA and lubricin may facilitate the transitions between lubrication modes by inducing hydrodynamic lubrication earlier.

Discussion: This study generated Striebeck curves to reveal the roles of HA and lubricin both alone and together throughout multiple modes of lubrication. HA was found to act primarily as a viscosupplement. It facilitated the transition between lubrication modes by increasing the lubricant viscosity. Changing viscosity either by chemistry or concentration generated data that fell along one Striebeck curve. Notably, the most viscous lubricant (HYADD) enabled the transition to full hydrodynamic mode lubrication, which has never been noted previously in unpressurized tissues. However, the boundary lubricant lubricin was effective in providing distinct Striebeck curves. A shift of the curve downward can be attributed to a boundary lubricant and both endogenous and exogenous lubricin were effective at reducing friction primarily in boundary mode conditions. The interaction between HA and lubricin was evident in the transitions between lubrication modes. The transition between mixed and hydrodynamic lubrication occurred at a much lower Hersey dimension when HA and lubricin were both present in the lubricating bath. The presence of lubricin effectively shifted the transition to hydrodynamic lubrication by a factor of 290 in the Hersey dimension.

Significance: This study used a Striebeck analysis to elucidate the mechanisms of lubrication and interaction of two key synovial
lubricants: lubricin and hyaluronic acid. Lubricin is an effective boundary lubricant, hyaluronic acid works as a viscosupplement, and interaction between the two lubricants may facilitate changes in lubrication mode.

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Figure 1: Left: Friction coefficient versus sliding speed for the three different HA conditions. Middle: Normalization of the sliding speed with lubricant viscosity and contact pressure to generate a Strubeck curve showing the modes of lubrication. Right: Dose response of HA (n = 3-5).

Figure 2: Friction coefficient versus Hersey dimension for different lubricin and HA conditions. Arrows indicate friction minima. (n = 2-5)

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